THE
JOURNAL OF GEOLOGY

A SEMI-QUARTERLY

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VOLUME XL

JANUARY–DECEMBER, 1932

1932
R 550 v.40

THE UNIVERSITY OF CHICAGO PRESS
CHICAGO, ILLINOIS

THE CAMBRIDGE UNIVERSITY PRESS, LONDON
THE MARUZEN COMPANY, LIMITED, TOKYO
THE COMMERCIAL PRESS, LIMITED, SHANGHAI

APR 18 1932

PUBLISHED FEBRUARY, MARCH, MAY, JUNE, AUGUST, SEPTEMBER,
NOVEMBER, DECEMBER, 1932

COMPOSED AND PRINTED BY THE UNIVERSITY OF CHICAGO
PRESS, CHICAGO, ILLINOIS, U.S.A.

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VOLUME XL NUMBER 1

THE
JOURNAL OF GEOLOGY

January-February 1932

KANSAS LACCOLITHS

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ABSTRACT

Woodson County in southeastern Kansas has been the scene of post-Douglas (Upper Pennsylvanian) intrusive igneous activity. Evidence of this is the presence of (1) an outcropping granite dike, (2) basic dikes or sills which were encountered by at least three drilled wells, and (3) hydrothermally metamorphosed rock in four separate bodies, one of which outcrops. The dikes and metamorphic rocks occur where the strata are folded into domes which are exceptionally sharp for Kansas. The writers suggest that the domal structure is due to the force of intrusion of magma into the deeper sedimentary rocks and that consequently these domes may properly be termed laccoliths.

INTRODUCTION

Three anticlines of unusual prominence in Woodson County, Kansas, have igneous phenomena associated with them. At one locality a dike of igneous rock is present at the surface and other dikes have been encountered in nearby drilled wells. No igneous rocks have as yet been discovered at or below the surface at the other two anticlines, but the sedimentary rocks have been severely altered by hydrothermal solutions, which fact strongly suggests the presence of underlying intrusive igneous rocks. There are, in addition, other areas in Woodson County and in northern Wilson County, which adjoins Woodson County on the south, in which some evidence has been found suggestive of nearby igneous activity.

The anticlines are domes of circular or elliptical plan. Although small in area, covering from four to six square miles only, they have closures as large as 140 feet. Such closures combined with the small

area produce dips of a magnitude which is very unusual in this region. This article stresses the apparently causal relationship between the anticlines and igneous intrusions and suggests that these structures could properly be termed laccoliths.

The location of Woodson County is shown on the index map of Kansas (Fig. 1) and that of the three anticlines within the county

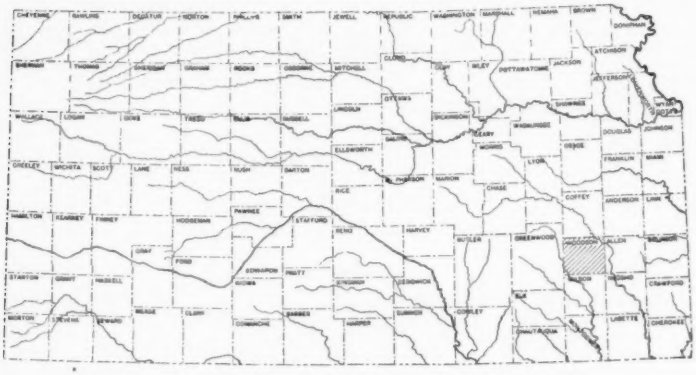

FIG. 1.—Index map of Kansas showing location of Woodson County

in Figure 2. Silver City dome and Rose dome are in southern Woodson County and the Neosho Falls dome is in northeastern Woodson County near Neosho Falls. The position of the Curtis well in which hydrothermally metamorphosed rocks were encountered is also given in Figure 2.

Two of the domes, Silver City and Rose, have already been described by Twenhofel and others.[1] The Neosho Falls dome has not heretofore been described. A brief review will be given in this paper of the Silver City and Rose areas while the Neosho Falls dome will be described in detail.

The writers acknowledge with appreciation the furnishing of pertinent data by W. L. Stryker of Fredonia, Kansas, and C. W. Studt,

[1] W. H. Twenhofel, "The Silver City Quartzites," *Bull. Geol. Soc. Amer.*, Vol. XXVIII (1917), pp. 419–30. W. H. Twenhofel and E. C. Edwards, "The Metamorphic Rocks of Woodson County, Kansas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. V (1921), pp. 64–74. W. H. Twenhofel, "Intrusive Granite of the Rose Dome, Woodson County, Kansas," *Bull. Geol. Soc. Amer.*, Vol. XXXVII (1926), pp. 403–12.

of Independence, Kansas. Samples from the Harris No. 8 well were supplied by Homer Charles of Bartlesville, Oklahoma.

DESCRIPTION OF INDIVIDUAL LACCOLITHS

SILVER CITY DOME

A structural map of the Silver City dome was published by Twenhofel and Edwards[1] in 1921. The anticline is elliptical in plan

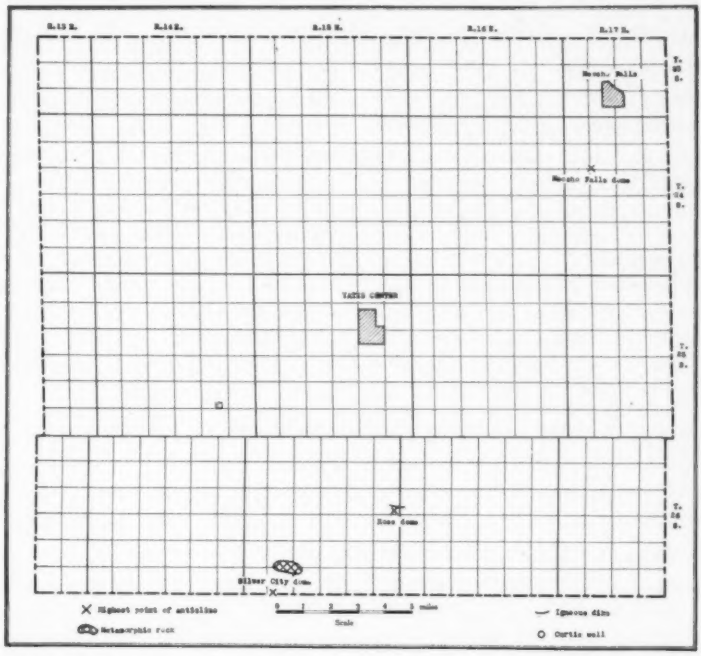

FIG. 2.—Map of Woodson County showing location of areas containing igneous phenomena.

with its major axis trending nearly due west. The greater part of the structure lies in Sec. 36, T. 26 S., R. 14 E.; Sec. 1, T. 27 S., R. 14 E.; Secs. 31–33, T. 26 S., R. 15 E.; and Secs. 4–6, T. 27 S., R. 15 E. The north flank of the dome has a short but prominent north-

[1] W. H. Twenhofel and E. C. Edwards, "The Metamorphic Rocks of Woodson County, Kansas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. V (1921), p. 65.

eastward trending spur, which extends from Section 32 into the southern half of Section 29. This "bulge" of the ellipse is especially interesting, for here occurs a mass of hydrothermally metamorphosed rocks, which in 1879 caused an entirely futile silver stampede. The center of the Silver City dome is a topographic basin, and the metamorphic rock crops out along the escarpment which forms the north rim of the basin.

The metamorphic rocks of the Silver City area were first described by Mudge[1] and Hay[2] in 1880 and 1882, respectively. Because of the mining development at the time of the visits of these geologists, they had a much better opportunity to study the rocks than is available today. Mudge writes:

> Some twenty shafts have been opened in the vain attempt to find valuable ores. These enabled us to obtain a most accurate knowledge of the metamorphic action. . . . . The moderate metamorphism was, in my estimation, clearly caused by the action of warm mineral siliceous waters, and probably under pressure. . . . . The vapors and hot waters had expelled a portion of the calcareous material of the limestone, and hardened it, by replacing the lost matter with silica. . . . . On the surface were masses of quartz containing clear, glassy crystals, and at one spot quite a number of specimens of beautiful amethyst. . . . . At a few places the stratum was twisted into small folds, as if the hot water had rendered it plastic and the pressure had caused it to yield.

No traces of silver or any other precious metals were found by Mudge. Hay observed that many beds had retained their horizontal position whereas others were considerably tilted. He identified the metamorphic rocks as mainly quartzite and breccia, but reached somewhat different conclusions from those of Mudge:

> We judge, then, that the metamorphic agency (heat) has been applied here from above, and under great pressure, and up to the point of fusion. This shaft yields, among other quartzose crystals, beautiful amethysts, and some that may possibly be beryl. . . . . This (micaceous dirt) is crossed in all directions by seams of dark blue or purplish stone of great hardness, from one to twelve inches thick. . . . . We regard the dark blue rock as the expression of the igneous agency. We think it is true igneous rock. We think long before other rocks were removed from the surface, this was pushed up from below into cracks and

[1] B. F. Mudge, "Metamorphic Deposit in Woodson County," *Trans. Kansas Acad. Sci.*, Vol. VII (1880), pp. 11–13.

[2] Robert Hay, "The Igneous Rocks of Kansas," *Trans. Kansas Acad. Sci.*, Vol. VIII (1882), pp. 14–18.

fissures probably finding here there was no outlet, in mass; but it may have ascended in places higher than the present surface, and spreading in small caverns altered patches of rock below it, and where there was room, causing a stream of half-melted material, which inclosed the fragments which now make the breccias. Again, the action of the igneous material would be likely long to have effect on the waters, and the thin veins of quartz and the crystals are probably due to infiltration in the cracks that were made as the mass cooled, while the micaceous dirt is perhaps altered shale.

Although the shafts were no longer open, Twenhofel[1] and Twenhofel and Edwards[2] examined both hand specimens and thin sections from material collected at the surface, some of which had been thrown out from the shafts, and found no igneous rocks. Furthermore, Twenhofel[1] reports that an examination of the cuttings from two wells drilled into the Silver City anticline revealed no igneous rocks, but did show the presence of highly altered sediments similar in character to those outcropping on the north flank of the structure. The following sentences give in abstract form certain data published by Twenhofel and Winchell.[3] The shales and sandstones have altered to gray and greenish quartzites, the green color being due to the presence of finely divided chlorite. Other minerals revealed by the microscope are orthoclase, sericite, kaolin, zircon, apatite, and magnetite. The limestones have been silicified to a hard black chert, which in places is brecciated and recemented by a matrix containing epidote and hornblende. Chlorite is present in the altered limestone and was also abundant in the samples obtained from the drilled wells.

The presence of cold water springs at Silver City is noted by Twenhofel and Edwards:[4] "Since the rocks are inclined northward from the springs it is probable that the water rises along fractures. A fault is said to occur in Sec. 2, T. 26 S., R. 14 E., and it is probable that there is a connection between this fault and the fracturing present in the hill." Fracturing was coincident with or antecedent to the ascent of the hot solution. The authors conclude ". . . . It is quite probable that intrusive igneous rocks may lie beneath the

[1] W. H. Twenhofel, "The Silver City Quartzites," *Bull. Geol. Soc. Amer.*, Vol. XXVIII (1917), pp. 419–30.

[2] W. H. Twenhofel and E. C. Edwards, *op. cit.*, pp. 64–74.

[3] *Op. cit.*, "The Silver City Quartzites."

[4] *Op. cit.*, p. 66.

Silver City ridge." Later Twenhofel[1] made this even stronger: "The metamorphism is readily accounted for by the assumption of an intrusive body of igneous rock beneath the surface."

ROSE DOME STRUCTURE

The Rose Dome structure and dikes have been mapped and discussed by Twenhofel[2] and Twenhofel and Edwards.[3] The dome is symmetrical with circular plan except on the northeast flank, where there is an eastward-plunging nose. A westward-striking granite porphyry dike crops out along the north flank of the dome. This dike has metamorphosed the sediments for a short distance from the contact. A well (Lieurance) drilled into the dome 300 yards northwest of the granite exposure encountered three zones of rocks containing pyroxene and dark brown mica at depths between 1,380 feet and 1,685 feet (the bottom of the well).[4] Twenhofel and Bremer are of the opinion that the mica and pyroxene "were derived from small basic dikes."[5] Diopside, found through a considerable vertical range in this well, is thought to be of contact metamorphic origin. A set of cuttings from the Eagle No. 1 well in southern Woodson County were examined by the same authors who state: "The samples studied indicate that a basic igneous rock was penetrated . . . . through a thickness of 102 feet, or from the depth of 1,151 feet to 1,253 feet."[6] The location of this well was given as in the SW. cor. of Sec. 31, T. 26 S., R. 16 E., which would place it about 3 miles south of the center of Rose dome. However, according to data given the writers by W. L. Stryker and verified by Charles Studt, the actual location of this well was in the center of the NE. $\frac{1}{4}$ of SW. $\frac{1}{4}$ of

[1] W. H. Twenhofel, "Intrusive Granite of the Rose Dome, Woodson County, Kansas," *Bull. Geol. Soc. Amer.*, Vol. XXXVII (1926), p. 410.

[2] "Granite Boulders in the Pennsylvanian Strata of Kansas," *Amer. Jour. Sci.*, Vol. CXCIII (1917), pp. 363–80; "Additional Facts Relating to the Granite Boulders of Southeastern Kansas," *Amer. Jour. Sci.*, Vol. CXCVIII (1919), pp. 132–35, and *ibid.*

[3] *Op. cit.*

[4] W. H. Twenhofel, "Intrusive Granite of the Rose Dome, Woodson County, Kansas," *op. cit.*, p. 409.

[5] W. H. Twenhofel and Bernard Bremer, "An Extension of the Rose Dome Intrusives, Kansas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. XII (1928), p. 758.

[6] *Ibid.*

Sec. 19, T. 26 S., R. 16 E., which places the well on the southeast flank of the Rose dome. Twenhofel and Bremer conclude that

> the contact metamorphic minerals and black rocks of the Lieurance well, the basic igneous rocks of the Southwestern Gas Company's well (Eagle No. 1), and the metamorphic rocks of Silver City are all manifestations of the intrusion of a large igneous body into the Pennsylvanian and older sediments at some date later than the deposition of the Pennsylvanian strata which now form the surface rocks of the region, and that the Rose dome granite porphyries represent the parent body and the black rocks minor intrusives therefrom.[1]

In an earlier paper describing the granite dike at Rose dome Twenhofel states: "This intrusion arched the strata intruded, led to the development of contact metamorphic minerals in favorable porous and frangible rocks, penetrated and baked shales for a short distance outward from the intrusion."[2]

Some additional data on the Rose dome have been obtained by the writers. Cuttings from the Tad Parsons well from a depth of 1,410–1,474 feet, furnished by W. L. Stryker, consist almost entirely of pyrite, quartz, and galena. The percentages of quartz and galena present are considerably less than that of the pyrite. Small crystals of sphalerite were observed in cuttings of the Rose well from a depth between 1,334 and 1,344 feet. The occurrence of hydrothermal galena and sphalerite about 70 miles distant from the northwest edge of the Tri-State zinc and lead mining district is of considerable interest.

An incomplete set of cuttings was examined from the Diver No. 1 well described as being in Sec. 18, T. 26 S., R. 16 E., which is on the east flank of the Rose dome. What is apparently an altered dike rock was encountered between 1,525 and 1,590 feet. This corresponds to the middle of the three "black rock" zones in the Lieurance well described by Twenhofel,[3] as occurring between 1,508 and 1,572 feet. The thickness of the zone is almost identical in the two wells. The fact that this altered igneous rock was encountered at practically the same level in the two wells suggests very strongly that the rock body is a sill instead of a dike. The most abundant constituent of the "black rock" is a very dense and dark-colored serpentine. Scattered

[1] *Ibid.*, p. 761.

[2] W. H. Twenhofel, "Intrusive Granite of the Rose Dome, Woodson County, Kansas," *op. cit.*

[3] *Ibid.*, p. 409.

through the serpentine are books of brittle mica, very fine grains of magnetite, and nearly colorless crystals of olivine. The olivine, as judged by its optical properties, is much closer to the forsterite than the fayalite end of the series. The igneous rock was evidently originally of basic or ultra-basic composition and was subjected to extensive hydrothermal metamorphism which caused the alteration of the pyroxene minerals to serpentine with the separation of magnetite and the alteration of biotite to brittle mica.

The presence of hydrothermal minerals was noted at a number of horizons in the Diver well. Cuttings from between depths of 1,000 and 1,030 feet contained a large amount of brown mica, quartz, pyrite, and actinolite. Cuttings from the 10 feet immediately overlying the serpentine consist of altered limestone with abundant brown mica. Cuttings from a depth between 1,600 and 1,602 feet, a short distance below the serpentine, consist of dolomitic marble, which contains abundant wollastonite and calcite and subordinate amounts of serpentine and brittle mica.

NEOSHO FALLS DOME

The Neosho Falls dome lies about 1 mile west and 1½ miles south of the town of Neosho Falls and covers parts of Secs. 7, 8, 17, and 18, T. 24 S., R. 17 E. It was mapped by one of the authors (Knight) in 1928. This map, contoured on the top of the Mississippian limestone, is reproduced in Figure 3. The top of the Mississippian lies at a depth of 1,150–1,200 feet. The rocks between the surface and the Mississippian are entirely of Pennsylvanian age. The surface formation is the Weston shale which lies at the base of the Douglas group in the upper Pennsylvanian. Elevations on the Mississippian were obtained by means of logs of wells drilled on the south half of the dome. The scarcity of wells on the north half of the dome necessitates the use of dashed contours in that area. However, the data given by wells drilled off structure to the northeast justify the conclusion that the contours close in that direction.

The dome is elliptical in plan with a general north and northeast trend. The dips are fairly high for the Mid-Continent area, amounting on the west flank to as much as 2°.

A well, known as the Southern Kansas Gas Company Harris No.

8, was drilled during December, 1927, and following months into the highest point on the Neosho Falls dome. This well is located 200 feet east and 200 feet north of the SW. corner of Sec. 8, T. 24 S., R. 17 E. The normal section of sediments was found in this well

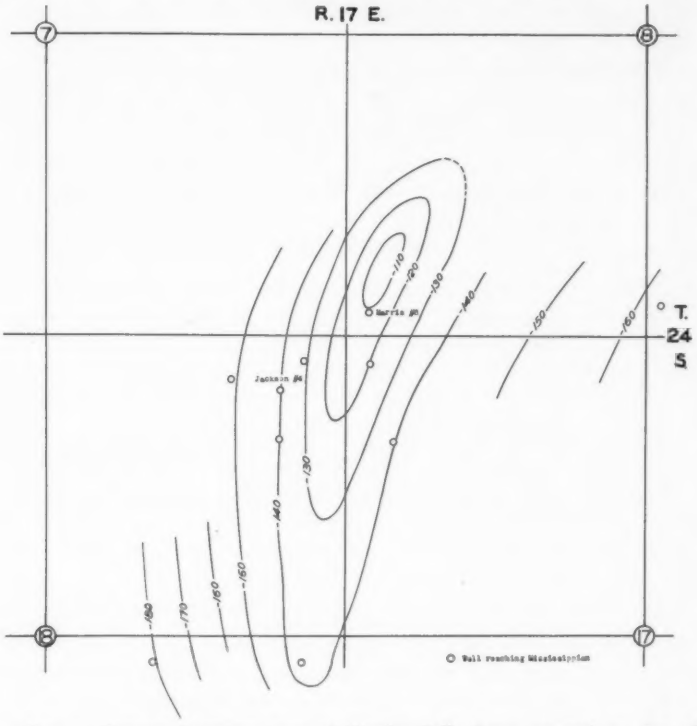

FIG. 3.—Structural contour map of Neosho Falls dome, mapped on top of Mississippian. Contour interval, 10 feet.

down to and including most if not all of the Mississippian formation. However, highly siliceous crystalline rocks were encountered immediately beneath the black shale lying between 1,410 and 1,415 feet. These do not occur normally in the local section. The cuttings from a depth of 1,380 feet—the base of the main body of the Mississippian limestone—and below were studied under the microscope. Their description follows:

1,380–1,385 Sheared fragments of white and gray fossiliferous limestone and limy shale. Small amounts of vein calcite, clear quartz, white chert, and pyrite.

1,395–1,400 Sheared white limestone, some black shale, pyrite, white chert, and clear calcite.

1,400–1,405 Gray and white limestone, silicified in part. White chert, black shale, vein calcite, and small amounts of pyrite and chalcopyrite.

1,410–1,415 Light gray limestone and dark shale that has been sheared. White opaline chert and considerable amounts of pyrite and chalcopyrite.

1,415–1,420 Dark shale, small amounts of chert. Most of the cuttings are composed of finely crystalline quartzitic material of various colors, being clear, pink, greenish, and gray to black. The gray and black or smoky color is caused by finely disseminated magnetite. The green color is produced by small crystals and crystalline masses of epidote or a closely related mineral mixed through the quartz rock.

1,420–1,425 Dark shale, masses of pyrite. Most of the cuttings consist of smoky, greenish, pink, and clear quartzite. Much finely disseminated magnetite.

1,425–1,430 Various colored quartzite, magnetite somewhat more coarsely crystalline. Few fragments of fine-grained silicified and dolomitized limestone.

1,430–1,435 Bulk of sample composed of quartzite, much of it is clear. Associated magnetite is coarser. Few bits of dark shale.

1,435–1,440 Clear to smoky quartzite with small amounts of the pink and green varieties.

1,450–1,455 Clear to smoky quartzite. Fine-grained magnetite. Pyrite, white chert.

1,455–1,460 Clear and smoky quartzite most abundant, pink and green plentiful. Considerable amounts of magnetite and scattering pieces of pyrite and white siliceous dolomitic limestone.

1,460–1,465 Clear to smoky quartzite with small amounts of the pink and green varieties. Small bits of chloritic material.

1,465–1,470 Clear to smoky quartzite with much magnetite.

1,470–1,475 Consists mostly of quartzite with small amounts of chert and silicified limestone fragments.

The hypothesis might be entertained that the Neosho Falls dome is underlain by a hill composed of metamorphosed pre-Cambrian rock which was encountered by the Harris well. However, neither the microscopic examination of the cuttings nor a megascopic examination of the larger fragments disclosed any evidence to support this view. No schistosity or rock cleavage could be recognized. On the other

hand, the greenish quartzite and the red jasper-like fragments found in the cuttings were strikingly similar to the metamorphosed material outcropping at Silver City and found in the cuttings of wells drilled on the Rose dome. It is reasonable to conclude that the deeper rocks encountered by the Harris No. 8 are metamorphosed post-Cambrian sediments. The Jackson No. 4 well, drilled on the southwest flank of the Neosho Falls dome about 1,200 feet from the Harris No. 8, penetrated similar stratigraphic depths but found instead of metamorphosed material the normal lithologic sequence of pre-Mississippian rocks.

The dominant processes in the metamorphism of the deeper rocks in the Harris well were the complete replacement by silica, mainly as crystalline quartz, and the introduction of a considerable amount of fine magnetite. As the sedimentary rocks are normally very low in iron, the magnetite was probably magmatic in origin, in which case the depositing solutions were of the high-temperature type. The presence of subordinate amounts of epidote, pyrite, and chalcopyrite is noted in the descriptive log above.

It is the writers' conclusion that the replacement of the sediments underlying the black shale by silica and magnetite was effected by solutions emanating from an underlying igneous mass, which, by the force of its intrusion produced the Neosho Falls dome. The black shale occurring between 1,410 and 1,415 feet was probably impervious to the magmatic solutions, thereby damming them and allowing complete replacement of the underlying beds, but protecting those above. This would account for the sharp change from sediments which show no metamorphism to those that are so completely changed that they have entirely lost their former identifying characteristics.

The association of quartz and magnetite among the material deposited by the hydrothermal solutions implies that the source magma must have been acidic. Veins associated with granite and consisting mainly of quartz and magnetite have been described by Spurr[1] and Miller.[2]

[1] J. E. Spurr, "Silver Plume Mining District," *U.S. Geol. Surv. Prof. Paper 63*, p. 182.

[2] William J. Miller, "Pegmatite, Silexite, and Aplite of Northern New York," *Jour. Geol.*, Vol. XXVII (1919), p. 41.

OTHER AREAS SHOWING EVIDENCE OF POSSIBLE IGNEOUS ACTIVITY

Cuttings from the Curtis *et al.* Boyer No. 1 well drilled in the SE. ¼ of Sec. 26, T. 25 S., R. 14 E., from a depth of 2,483–2,506 feet were highly silicified and contained disseminated magnetite. They are very similar in appearance and composition to those obtained in the Harris No. 8 well described above. No data are at hand regarding the geologic structure of the area surrounding the Curtis well.[1]

W. L. Stryker, petroleum geologist of Fredonia, Kansas, has observed some other phenomena suggestive of igneous activity. The cuttings from a well drilled in the NE. cor. of Sec. 34, T. 26 S., R. 15 E., contained some very large mica plates. Wells drilled on a fairly sharp anticline in the southwest part of Section 10 and in the northwest part of Sec. 15, T. 27 S., R. 15 E., northern Wilson County (about 4 miles southeast of the Silver City dome) encountered not only large plates of mica but also asphalt in a deeply buried sandstone. The large mica flakes may have been deposited by hydrothermal solutions emanating from an igneous mass. The asphalt is perhaps a residual product of petroleum which at one time filled the interstices in the sandstone, but later suffered a natural distillation caused by magmatic heat.

Other intrusive rocks in the Plains area have been described by Gould.[2] Kansas contains but two areas of outcropping intrusive igneous rock. One of these, the granite dike on the north flank of Rose dome, has already been described. The other is a porphyritic peridotite in the form of a small volcanic neck or pipe of post-Permian age in west-central Riley County, Kansas.[3] A single exposure of pegmatitic igneous rock occurs in Camden County, south central Missouri. Edward M. Shepard, in a personal communication to C. N. Gould, states:

[1] Subsequent to the writing of this manuscript the writers have seen a structural map of the area surrounding the Curtis well, through the courtesy of Marvin Lee and J. L. Garlough. The Curtis well was drilled on the top of a well-defined dome which has a closure of approximately 25 feet and a structural relief of about 60 feet.

[2] Charles N. Gould, "Crystalline Rocks of the Plains," *Bull. Geol. Soc. Amer.*, Vol. XXXIV (1923), pp. 541–60.

[3] R. C. Moore and W. P. Haynes, "An Outcrop of Basic Igneous Rock in Kansas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. IV, No. 2 (1920), pp. 183–87.

The pegmatite exposure in Camden County is, without any doubt in my mind, a volcanic dike. The immediate contact with adjoining rocks shows metamorphism in the formation of beautiful yellow, contorted muscovite, schist and quartzite. The galena in the neighborhood is badly decomposed. The rocks for many acres around, representing the lower formations, either stand on edge or are greatly tilted.[1]

C. L. Dake has recently expressed the opinion that this pegmatite body is the top of a pre-Cambrian knob.[2]

A very interesting area in southern Prowers County, southeastern Colorado, was described by Professor R. D. George in a personal communication to C. N. Gould as follows:

South of Lamar there is a laccolithic area in the southeastern part of township 27 south, range 46 west. The main part of the igneous area is in section 35, but extends over into section 36, and, according to a new survey made, may extend into sections 1 and 2 of township 28 south, range 46 west. The rocks of the main laccolithic bodies are very basic syenitic types. . . . . Associated with the laccoliths are 50 or more dikes of various lengths and touching the adjacent corners of the four townships. On one of these areas is a body of porphyritic granite . . . . 100 yards long and 15 to 20 yards wide. Gilbert,[3] says: "Fragments of various rocks are included in the laccoliths and dikes, and are of interest as revealing the nature of the lower lying terranes through which the ascending liquid passed. Besides sandstones and shales similar to those constituting the wall rocks, the most abundant as well as the most notable rock is a porphyritic granite with conspicuous crystals of gray feldspar." This suggests his belief that the granite is an inclusion in or mass floated up by the basic igneous rocks forming the laccolith. There are at least three granite laccoliths, but I am not entirely certain that the two smaller granite masses are in place. While I have made no petrological examination of the granite, its general appearance suggests quartz monzonite rather than a true granite.[4]

The continued use of the word "laccolith" in this description is worthy of note.

Igneous dikes occur in southeastern Missouri, southern Illinois and Kentucky. Those in Missouri were described by Weller and St. Clair[5] and classified as olivine kersantite. He follows his rock de-

[1] Gould, *op. cit.*, p. 548. [2] Oral communication, September, 1928.

[3] G. K. Gilbert, "Laccolites in Southeastern Colorado," *Jour. Geol.*, Vol. IV (1896), p. 821.

[4] Gould, *op. cit.*, pp. 549–50.

[5] Stuart Weller and Stuart St. Clair, "Geology of St. Genevieve Co., Missouri," *Mo. Bur. Geol. and Mines*, 2d ser., Vol. XXII (1928), pp. 249–50.

scriptions with this observation: "South of Saline Creek there are several small areas where the Bonneterre rocks have a peculiar doming which may have been caused by an intrusion which has not yet been exposed at the surface by erosion." The occurrence of intrusive sills, necks, and dikes along the coastal plains border in Arkansas and Texas is well known.

AGE OF IGNEOUS ACTIVITY

No sedimentary formations are present in Woodson County younger in age than the igneous dikes and the hydrothermal metamorphism, so the age of the igneous activity cannot be determined with any exactitude. The sediments belong to the Douglas group (Upper Pennsylvanian) and the intrusions are consequently post-Douglas. Twenhofel notes the large size of grain in the granite porphyry dikes, and concludes that evidently a thick cover was present which has been subsequently removed by erosion so the intrusions took place during the Tertiary or even earlier.[1] The writers can add no factual data to this discussion.

CONCLUSIONS

The writers believe that the relationship between the described domes in Woodson County, Kansas, and intrusive igneous activity is sufficiently close to justify the conclusion that the latter caused the doming by pushing up of the sedimentary strata. In one of the three anticlines, the Rose dome, both acidic and basic igneous dike rocks occur. In the other two no igneous rock occurs at the surface and none as yet has been encountered in wells, but the presence of hydrothermally metamorphosed sediments along with the unusually steep dips of the anticlines is strong evidence for the presence of intrusive igneous rocks underlying the structures.

The hypothesis presented is that a parent body of magma first intruded the crystalline shell underlying Woodson and adjacent counties. Cupolas on the top of this deep-seated igneous body broke through the pre-Cambrian rocks and arched the overlying sedimentary strata at the same time sending out dike offshoots. With crystallization of the magma in the cupola, hydrothermal solutions were

[1] "Intrusive Granite of the Rose Dome, Woodson County, Kansas," *op. cit.*

expelled which worked upward through the rocks causing metamorphism of the shales, sandstones, limestones, and some of the dikes.

Due to the tendency of anticlinal folds to diminish in structural height upward, the closure in the strata immediately overlying the intrusive is undoubtedly greater than the closure in the surface formations. Correspondingly, the flanks of the intrusive and the immediately overlying strata must dip more steeply than do the surface rocks.

Although the term "laccolith" originally designated a lens-shaped body of igneous rock with arched overlying sediments, it has been applied in recent years to igneous bodies which are, or were before erosion, overlain by dipping strata, but where data as to the character of the lower part are unavailable. The authors believe that the evidence in Woodson County of igneous rock beneath the sharp domes and the causal relationship between the two is sufficiently strong to justify the term "laccolith" here.

The additional evidence of igneous activity in southeastern Kansas presented in this paper, may prove of interest to those following the recent trend in regarding the Tri-State zinc and lead deposits to be of hydrothermal origin.

ALTERATION AS AN END PHASE OF IGNEOUS INTRUSION IN SILLS ON LOVELAND MOUNTAIN, PARK COUNTY, COLORADO[1]

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ABSTRACT

Sills occurring in the sedimentary rocks on the lower slope of Loveland Mountain belong to two rock types of slightly different ages. Monzonitic-diorite porphyry is the older; quartz-monzonite porphyry, the younger. They are derived from the same magma reservoir, and are composed of different proportions of the same minerals. The groundmass of the quartz-monzonite porphyry is very acidic. Although the sedimentary rocks between them are unaltered, both porphyries are altered. However, the monzonitic-diorite porphyry is comparatively fresh, whereas the quartz-monzonite porphyry is intensely altered. The principal products of alteration are albitized plagioclase, sericite, penninite, epidote, white carbonate, and iron-carbonate. They were introduced progressively. Evidence indicates that the alteration of each porphyry was an end stage of its intrusion and that the agents of alteration were in the magma itself or followed the same paths as the magma. It is suggested that the term "deuteric" be restricted to reactions in a closed system and not applied to alterations of the type described here.

INTRODUCTION

Recent geological literature reveals among both economic geologists and petrologists a growing recognition of the importance of alteration occurring as an end phase of igneous intrusion. An excellent example of such alteration in sills intruded into a series of sedimentary rocks is found in an area of about 1½ square miles on the lower slope of Loveland Mountain, near Alma, Colorado. The location of the area is shown in Figure 1.

Material for this paper was obtained while the writer, under the direction of B. S. Butler, was engaged in work for the United States Geological Survey in co-operation with the state of Colorado and the Colorado Metal Mining Fund. To all members of the United States Geological Survey engaged in Colorado work, and especially to Mr. B. S. Butler and Mr. T. S. Lovering, the writer is grateful for many suggestions regarding the petrology of the igneous rocks. To Dr. Harold L. Alling, of the University of Rochester, Drs. Ed-

[1] Published by permission of the director of the United States Geological Survey. This paper was presented in outline form at the meetings of the G.S.A., December 31, 1930.

ward B. Mathews and Joseph T. Singewald, Jr., of the Johns Hopkins University, and to Mr. G. F. Loughlin and Mr. C. S. Ross, of the United States Geological Survey, the writer is indebted for helpful criticism of the paper.

GENERAL GEOLOGY OF THE AREA

A very brief account of the general geology is presented to serve as a background for the petrologic data. A more complete description of the sedimentary rocks, accompanied by an areal geologic map, has been published.[1] The pre-Cambrian basement rocks con-

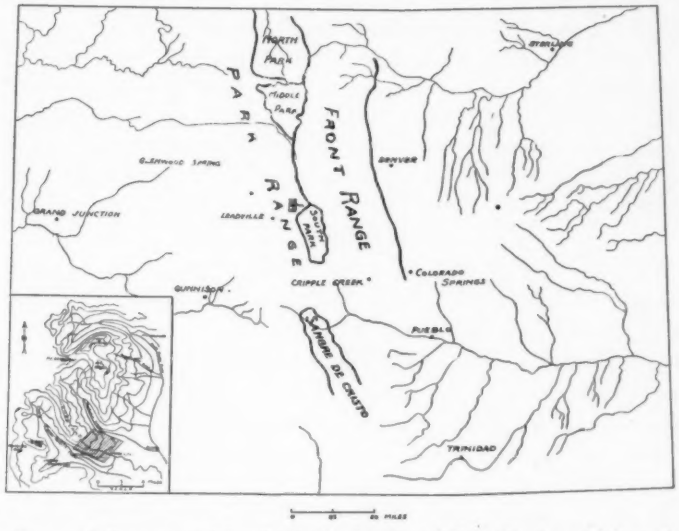


FIG. 1.—Index map of Colorado showing location of Alma District, with insert index map of Alma District showing location of Loveland Mountain area.

sist of injection gneiss, quartz-mica schist, and pegmatite. Upon these lie a series of concordant sedimentary strata ranging in age from Cambrian to Pennsylvanian. Minor intrusives of Tertiary (?) age, which form part of the intrusive belt[2] of central Colorado that

[1] Q. D. Singewald and B. S. Butler, "Preliminary Geologic Map of the Alma Mining District, Colorado," *Colo. Sci. Soc. Proc.*, Vol. XII (1930), pp. 295–308.

[2] J. E. Spurr and G. H. Garrey, "Economic Geology of the Georgetown Quadrangle (together with the Empire district), Colorado, with General Geology by S. H. Ball," *U.S. Geol. Surv. Prof. Paper 63* (1908), pp. 67–71.

extends southwestward from Boulder County, occur mainly as dikes in the pre-Cambrian rocks and as sills in the Paleozoic strata. The principal structural features are the regional dip of the sedimentary strata of about 15° to the east-southeast and the numerous faults. Most of the faults have short lengths and small displacements. Faulting was inaugurated before, and lasted until long after, intrusion of the Tertiary (?) igneous rocks.

TERTIARY (?) INTRUSIVES

Tertiary (?) intrusives within the area belong to two main classes of slightly different ages. They are designated as quartz-monzonite porphyry and monzonitic-diorite porphyry. The name applied to the first class is self-explanatory. The second class was described originally as porphyrite,[1] and later as diorite-porphyrite,[2] but the term "porphyrite" is no longer used by the United States Geological Survey. Rocks of this class have a distinct monzonitic tendency, but the term "diorite" is retained because it is firmly intrenched in local usage.

The sills illustrate the kind of alteration under consideration so much more clearly than the dikes that they alone are considered. Six sills—four of quartz-monzonite porphyry and two of monzonitic-diorite porphyry—occur in the sedimentary rocks on Loveland Mountain. Three of the sills, two of quartz-monzonite porphyry and one of monzonitic-diorite porphyry, are in the quartzite member of the Sawatch (Cambrian) formation, the lowest sedimentary formation of the region. These are of particular interest because they occur close together and are enclosed in the same kind of sedimentary rock. The total thickness of the sediments in the area is about 600 feet. Individual sills range from 15 to 40 feet in thickness.

PETROGRAPHY

The petrographic descriptions that follow apply to the rocks where they have not been affected by ore-forming solutions or by processes of weathering. These effects will be discussed in the final report on the Alma district, but they are of no concern in this paper.

[1] S. F. Emmons, "Geology and Mining Industry of Leadville, Colorado," *U.S. Geol. Surv. Mono. 12* (1886), p. 85.

[2] H. B. Patton, A. J. Hoskin, and G. M. Butler, "Geology and Ore Deposits of the Alma District, Park County, Colorado," *Colo. Geol. Surv. Bull. 3* (1912), p. 85.

Megascopic features.—The most distinguishing features of the monzonitic-diorite porphyry, as compared with the quartz-monzonite porphyry, are its dark-green color, fresh appearance, abundance of phenocrysts, especially hornblende, and the almost total absence of visible quartz. In the monzonitic-diorite porphyry, profuse phenocrysts of glassy plagioclase, shiny hornblende, scattered glistening biotite, and rare quartz are imbedded in a dense, dark-green groundmass. In the quartz-monzonite porphyry, numerous phenocrysts of altered feldspar, quartz, and green pseudomorphs after former ferromagnesian minerals, are imbedded in a dense, medium-green groundmass whose color obviously is due to disseminated chlorite. The phenocrysts range in size from fine-grained to medium-grained.

Microscopic features.—Both rocks are porphyritic with a distinct break in grain size between the phenocrysts and the groundmass. Phenocrysts in the monzonitic-diorite porphyry comprise from one-fourth to one-third of the rock mass. Although they are but slightly less abundant in the quartz-monzonite porphyry, many, whose outlines are distinguishable in thin section, are replaced by fine-grained mineral aggregates and are not recognizable megascopically.

A summary of the mineralogy of the two porphyries is given in Table I. The inferred mineral composition before alteration is tabulated under the heading "Original Minerals," with the minerals arranged in their order of abundance from left to right. For each rock, a word describing the extent of alteration and a list of the alteration products for each principal mineral except quartz are tabulated under the heading "Alteration Minerals." The "alteration minerals" were formed after complete consolidation of the rock; albitization, although really an alteration, is included under "original minerals," because it may have occurred before consolidation.

Plagioclase phenocrysts in both rocks occur as short prisms—0.2 mm. to 2.5 mm. in length—most of which are subhedral but a few of which are either euhedral or fragmental. Occasional grains consist of several individuals grown together. Crystals exhibiting oscillatory zoning, which range in composition from sodic labradorite to intermediate andesine, are abundant where the feldspar has not been albitized. Where the composition of the plagioclase

phenocrysts is close to Ab_9An_1 no unchanged remnants of andesine exist. The plagioclases enclose small and sparsely scattered crystals of the accessory minerals, and very rarely, biotite. Alteration minerals, on the whole, impregnate the outer rim and leave the interior relatively unaltered; in a few instances, however, they impregnate either certain of the twins or the interior portion of the grain and leave the rest relatively unaltered. A few thin sections

TABLE I

MINERAL CONTENT OF THE PORPHYRIES

ORIGINAL MINERALS

	MONZONITIC DIORITE PORPHYRY				
PHENOCRYSTS	ANDESINE (Close to Ab_3An_2) (Rarely albitized)	HORNBLENDE	BIOTITE	QUARTZ (Rare)	
ACCESSORY MINERALS	TITANIFEROUS MAGNETITE	APATITE	TITANITE	ZIRCON	
GROUNDMASS	SODIC PLAGIOCLASE	ORTHOCLASE	HORNBLENDE	BIOTITE	QUARTZ

	QUARTZ MONZONITE PORPHYRY				
PHENOCRYSTS	ANDESINE (Close to $Ab_{33}An_{67}$) (Almost everywhere albitized)	BIOTITE	QUARTZ	HORNBLENDE	
ACCESSORY MINERALS	APATITE	TITANIFEROUS MAGNETITE	ZIRCON	TITANITE	ALLANITE (Rare)
GROUNDMASS	QUARTZ	ORTHOCLASE	SODIC OLIGOCLASE (Close to Ab_9An_1)		BIOTITE

ALTERATION MINERALS

ORIGINAL MINERAL		PLAGIOCLASE	HORNBLENDE	BIOTITE	ORTHOCLASE
MONZONITIC-DIORITE PORPHYRY	EXTENT ALTERED	MODERATELY	MODERATELY	SLIGHTLY	SLIGHTLY
	ALWAYS PRESENT	SERICITE WHITE CARBONATE	PENNINITE WHITE CARBONATE EPIDOTE LEUCOXENE	GREEN MICA PENNINITE LEUCOXENE	SERICITE WHITE CARBONATE
	OCCASIONALLY PRESENT	EPIDOTE PENNINITE QUARTZ		EPIDOTE RUTILE	
QUARTZ MONZONITE PORPHYRY	EXTENT ALTERED	INTENSELY	COMPLETELY	ALMOST COMPLETELY	MODERATELY
	ALWAYS PRESENT	SERICITE WHITE CARBONATE	PENNINITE WHITE MICA WHITE CARBONATE LEUCOXENE	PENNINITE WHITE MICA WHITE CARBONATE LEUCOXENE	SERICITE WHITE CARBONATE
	OCCASIONALLY PRESENT	PENNINITE EPIDOTE ZOISITE IRON CARBONATE QUARTZ	EPIDOTE IRON CARBONATE	EPIDOTE IRON CARBONATE RUTILE QUARTZ	

contain highly altered plagioclases, with fresh ones near by. In the monzonitic-diorite porphyry the plagioclase is more highly altered than the ferromagnesian minerals, but in the quartz-monzonite porphyry it is less altered than the ferromagnesian minerals.

Common green hornblende phenocrysts, in which the extinction angle $Z \wedge c$ is 25°, in the monzonitic-diorite porphyry form subhedral or fragmental prisms, either stout or slender, which have a maximum length of 8.0 mm. They enclose grains of the accessory minerals, particularly magnetite and apatite, as well as a few of biotite and andesine.

Brown biotite phenocrysts in the monzonitic-diorite porphyry oc-

cur as isolated prisms and fragments of hexagonal plates and as intergrowths with or inclusions in hornblende and even plagioclase. Inclusions of the accessory minerals are less abundant than in hornblende.

The ferromagnesian phenocrysts in the quartz-monzonite porphyry, except for rare inclusions of brown biotite in plagioclase, are completely replaced by alteration minerals. The occurrence of sagenitic rutile in many of the pseudomorphs indicates that biotite originally predominated; but the slender, almost euhedral, prismatic form of others seen megascopically throughout the rock suggests that hornblende also existed. The alteration minerals apparently first developed within the original mineral and then extended outward with irregular boundaries into the groundmass.

Quartz phenocrysts are found in only a few thin sections of the monzonitic-diorite porphyry, but always are an important constituent in those of the quartz-monzonite porphyry. The grains range from 0.2 mm. to 3.0 mm. in diameter. They are nearly always embayed by the groundmass and here and there have cracks healed by groundmass material. Most of them in the quartz-monzonite porphyry are surrounded by rims of optically continuous groundmass quartz. Glass (?) and fluid inclusions, some containing moving bubbles or salt (?) crystals, are abundant; but mineral inclusions of tiny apatites and zircons are rare. The quartz itself is unaltered, but cracks are commonly healed by secondary minerals, particularly sericite.

Titaniferous magnetite occurs as small euhedral crystals scattered uniformly throughout the rock, larger and somewhat skeletal masses intergrown with other accessory minerals, and grains included in the ferromagnesian phenocrysts. The larger aggregates attain diameters of almost a millimeter. Some grains are slightly altered to leucoxene. Many magnetites in the quartz-monzonite porphyry are surrounded by clusters of penninite, and sericite, and, rarely, fibrous, green biotite. The penninite and sericite probably are alteration products of biotite which, as will be explained when describing the groundmass, probably formed through interaction of the magnetite with the groundmass. Therefore, in the quartz-monzonite porphyry, magnetite probably was more abundant originally than now.

Apatite occurs in grains ranging from tiny needles to stout subhedral or broken prisms having lengths as much as 0.4 mm. The larger grains are isolated crystals that could be regarded as phenocrysts; medium-sized grains are isolated and also are included in hornblende, biotite, and the magnetite aggregates; tiny needles have the same occurrence as the medium-sized grains and, in addition, are included in feldspar and quartz.

Primary titanite grains, ranging in diameter from 0.02 mm. to 0.35 mm., are occasionally wedge-shaped but more often anhedral. Most of them are isolated, but a few are included in magnetite aggregates or hornblende. Primary titanite in the monzonitic-diorite porphyry is much less abundant than apatite and in the quartz-monzonite porphyry is rare.

Small euhedral zircons occur as inclusions in the phenocrysts and, occasionally, as isolated grains.

Allanite forms large subhedral grains, with a maximum length of 1.5 mm. It is present in only a few thin sections of the quartz-monzonite porphyry.

The groundmass of the monzonitic-diorite porphyry has typically microgranular fabric. Grains in general appear more or less equigranular but range in diameter between the extreme limits of 0.005 mm. and 0.1 mm. Anhedral hornblende prisms and biotite flakes are intergrown with more or less rounded feldspars and quartz. There is only a small amount of quartz. The amount of biotite varies considerably, but is never in excess of hornblende. Hornblende is considerably less abundant than feldspar. The feldspar consists of both sodic plagioclase and orthoclase; but as many of the plagioclases are untwinned, they are difficult to distinguish from orthoclase. Alteration of the groundmass is less intense than that of the phenocrysts, but the products are the same. In the groundmass the ferromagnesian minerals are more altered than feldspars.

The groundmass of the quartz-monzonite porphyry varies in fabric, even in the same sill, from micro-granular, in which a few semi-microporphyritic feldspars are surrounded by anhedral grains of all the minerals, to micro-poikilitic, in which rounded quartz masses enclose feldspar and biotite. Where it is micro-granular, the average diameters of the grains range in different specimens from

0.005 mm. to 0.03 mm.; where it is micro-poikilitic, feldspar and biotite grains are still smaller. but are enclosed in rounded quartz aggregates with diameters of as much as 0.3 mm. Although quartz in both varieties appears as rounded interstitial grains in plain light, nearby grains in the micro-poikilitic variety extinguish together between crossed nicols. The feldspars occur mostly as formless grains, but a few are subhedral equant to lath shaped.

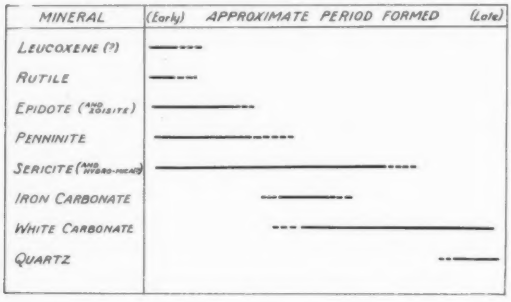
Biotite, now almost completely altered, is much less abundant in the groundmass than feldspar. Its flakes occur isolated, fringe the ferromagnesian phenocrysts, surround magnetite grains, and form veinlets that usually extend out from the iron-bearing minerals. Some of the veinlets cut through the groundmass in such a manner as to prove they formed after consolidation. On the other hand, in less altered rocks elsewhere in the Alma district, biotite flakes that fringe hornblende and biotite plenocrysts and form replacement masses within hornblende boundaries are exactly like other biotite flakes that occur intergrown with feldspar and quartz in a micrographic groundmass. The biotite in these rocks appears to have formed in part by reaction before consolidation between ferromagnesian phenocrysts and the groundmass. Hence, the distribution of the groundmass biotite in the quartz-monzonite porphyry, both in the rocks on Loveland Mountain and in the rocks elsewhere in the Alma district, indicates it formed in part by interaction of the groundmass, magnetite, and ferromagnesian phenocrysts, and the magma residuum. The interaction probably began before and continued until after consolidation.

Alteration.—Evidence presented in the ensuing paragraphs, obtained principally by comparing thin sections showing different degrees of alteration in the same rocks throughout the Alma district, indicates that the alteration minerals were introduced gradually and in a normal sequence (see Table II), that may be divided into three stages. Albitization was the first stage. It was followed by the introduction of sericite and small amounts of epidote, zoisite, and penninite into the feldspars; of penninite, epidote, small amounts of sericite, and leucoxene (?) into the hornblendes; and of penninite, epidote, white mica, leucoxene (?), and rutile into the biotites. Pyrite was probably introduced before the close of the second stage,

and iron carbonate at the end of it. There is no petrographic evidence to prove that some white carbonate was not introduced during this stage, but it is improbable that the temperature was sufficiently low to permit it. In the further alteration of the third stage, white carbonate and more sericite were introduced, replacing feldspar, remnants of the ferromagnesian minerals, epidote, and penninite. Epidote was less stable than penninite. Introduction of more white carbonate and a very small amount of quartz completed the process.

TABLE II

DIAGRAM SHOWING RELATIVE AGES OF ALTERATION MINERALS
(FORMED SUBSEQUENT TO ALBITIZATION)



The plagioclase phenocrysts in the quartz-monzonite porphyry throughout the Alma district have a composition of about Ab_9An_1 where the rock is highly altered, and about $Ab_{55}An_{45}$ where alteration is less intense; yet there are exceptions. In the monzonitic-diorite porphyry, which everywhere is comparatively fresh, phenocrysts with a composition of about Ab_9An_1 are found in only a few thin sections. Hence, phenocrysts with a composition of Ab_9An_1 in either porphyry may be attributed to albitization of an original andesine at an early stage of the alteration cycle. There is no evidence to prove whether it took place before or after complete consolidation.

The presence of epidote and its mineral associations furnish the best means for separating the second from the third state of the alteration. In rocks containing epidote the plagioclases are less al-

tered than in those that do not. The plagioclases of the latter contain more white carbonate and a little more sericite. In rocks containing epidote the ferromagnesian pseudomorphs consist chiefly of penninite, epidote, and relatively coarse-grained white-mica (hydromica), with little or no white carbonate or sericite. The epidote forms irregular masses, which are most abundant in the interior of the pseudomorphs. In thin sections containing very little epidote are found masses having similar outlines and distribution but filled with white carbonate; where such carbonate occurs with epidote, sericite interfingers with the associated penninite. This is regarded as an early step of the third stage. Where no epidote exists, there is less penninite and more white carbonate and sericite.

In addition to replacement masses having irregular outlines, occasional veinlets of white carbonate with a little quartz penetrate the rock in a manner that proves they are the last-formed constituents.

COMPARISON OF THE PORPHYRIES

Certain similarities and certain differences of the two porphyries are apparent from the detailed petrographic description and from examination of Table I. The same minerals constitute the phenocrysts in each, but their proportions are different. In the quartz-monzonite porphyry, the plagioclase is very slightly more sodic, the ratio of biotite to hornblende is much higher, and quartz is more abundant than in the monzonitic-diorite porphyry. Although in both types the phenocrysts, when considered alone, comprise an igneous rock of intermediate composition, the phenocrysts of the quartz-monzonite porphyry are the more felsic. Textural characteristics of each mineral are identical in both rocks; moreover, grains consisting of several feldspars grown together and locally including biotite are fairly common in both.

Except for allanite, which is very sparsely distributed in the quartz-monzonite porphyry, the accessory minerals are the same in both rocks, but their relative order of abundance is different. If allowance is made in the quartz-monzonite porphyry for magnetite probably lost by interaction with the groundmass, the only essential difference between the accessory minerals of the two types is the ratio of zircon to titanite. Texturally, each mineral is identical in

both types. This general similarity and the field evidence of close similarity in age favor the conclusion that both rocks have been derived from the same magma reservoir and that both the phenocrysts and the accessory minerals are of intra-telluric origin.

The groundmass of the monzonitic-diorite porphyry was more salic than the phenocrysts, but they were nearly in equilibrium. The minerals of its groundmass alone are those of a quartz monzonite. The groundmass of the quartz-monzonite porphyry was richer in quartz and alkalic feldspars and not in equilibrium with the phenocrysts, so that interaction ensued. The minerals of the groundmass, with the exception of biotite formed through interaction, are nearly equivalent to a monzonite-aplite.

Both rocks everywhere show evidence of alteration subsequent to consolidation; but the monzonitic-diorite porphyry is only slightly altered, whereas the quartz-monzonite porphyry is intensely altered. The comparative freshness of the monzonitic-diorite porphyry is evident in the field and has been noted by both Emmons[1] and Patton.[2] It has been further substantiated by a petrographic study of specimens, from each of the sills, collected directly above one another on cliff exposures. The alteration minerals range from high to medium temperature products. Table I shows that each original mineral contains the same alteration products in both rocks but is more highly altered in the rock having the more sodic groundmass. The rock having the more sodic groundmass probably crystallized from the magma having the greater quantity of "mineralizers."

AGE RELATIONS OF THE PORPHYRIES

Although petrographic and structural evidence indicate that the two porphyries are closely related in source and age, they have not been found in contact with each other within the small area under discussion. Elsewhere in the Alma district, however, a rock closely allied to the monzonitic-diorite porphyry, though a little more salic, is cut by quartz-monzonite porphyry, and a regional study of igneous rocks in the Tertiary (?) intrusive belt of Colorado by Lovering[3] has shown that rocks of the monzonitic-diorite class are older than the quartz-monzonite porphyries.

[1] S. F. Emmons, *op. cit.*

[2] H. B. Patton, *op. cit.*

[3] T. S. Lovering, oral communication.

Local petrographic data accord with this regional evidence. As the groundmass of each porphyry is more salic in composition than its phenocrysts, crystallization in the magma reservoir was in the direction of calcic to sodic; and it follows that the more sodic of the two porphyries, the quartz-monzonite, should be the younger.

CONCLUSIONS REGARDING ALTERATION

The foregoing data, together with the fact that the sedimentary rocks show no sign of alteration comparable to that in the porphyries, lead to the following conclusions:

1. The agents causing alteration were contained in each intruding magma itself and followed the same paths as the intruded porphyry.

2. Alteration was an end phase of the intrusion cycle of each porphyry. Had it been separated by an appreciable time interval, faulting would have provided the agents of alteration with channels of ascent other than those taken by the magma, just as it provided other channels of ascent for later ore-bearing solutions.

3. As it is improbable that mineralizers contained only in the magma within the sills themselves were sufficiently abundant to cause the intense alteration of the quartz-monzonite porphyry, it seems likely that mineralizers within the sills were augmented by mineralizers from more deep-seated magma before complete consolidation in the conduits that acted as feeders to the sills.

DEUTERIC OR HYDROTHERMAL?

The question naturally arises: Shall these alterations be classed as deuteric or hydrothermal? Up to this point, the writer has purposely avoided the use of these terms, because the alterations lie close to the dividing line and their classification as one or the other depends, not upon interpretation of geological facts, but upon broad or restricted uses of the terms "deuteric" and "hydrothermal metasomatism."

Schaller[1] has divided igneous processes into two classes: (1) magmatic and (2) hydrothermal. In the magmatic, liquidity is due principally to heat, and the system is essentially closed. In the hydrothermal, liquidity is due principally to the presence of a solvent,

[1] W. T. Schaller, "Mineral Replacements in Pegmatites," *Amer. Mineralogist*, Vol. XII (1927), p. 59.

and the system is open. Ross,[1] who discussed the idea of closed and open systems, pointed out that "the term 'hydrothermal solution' means hot water that contains dissolved materials, but it implies nothing about the source, nature, or degree of concentration of these materials." The alterations described in this paper, with the possible exception of the albitization of andesine, are those of an open system and were accomplished by hydrothermal solutions of magmatic origin.

On the other hand, the alterations occurred as an end phase of the intrusive cycle. The sequence for each porphyry was intrusion of magma containing intra-telluric minerals, crystallization of the groundmass, and hydrothermal alteration. The cycle was completed before the intruding rock had cooled to the temperature of the invaded rock. Therefore, some geologists would regard the alterations as deuteric. A recent discussion[2] in *Economic Geology*, however, shows there is a disagreement among geologists regarding correct usage of the term "deuteric." The deuteric reactions originally described by Sederholm[3] were caused by either a water-rich magma residuum or a concentrated hydrothermal solution, but the system was essentially a closed one. Colony[4] extended the term and described reactions produced at high temperatures in an open system; some of the reactions were the end stage of an intrusion that occurred not as a single event but by continuous renewal of magma from below. Gillson extended the term still further and used it in several papers, in two[5] of which "deuteric" included reactions pro-

[1] C. S. Ross, "Physico-chemical Factors Controlling Magmatic Differentiation and Vein Formation," *Econ. Geol.*, Vol. XXIII (1928), pp. 868–69.

[2] J. L. Gillson, "On the Use of the Term Deuteric," *Econ. Geol.*, Vol. XXIV (1929), pp. 100–102; F. F. Osborne, "On the Use of the Term Deuteric," *Econ. Geol.*, Vol. XXIV (1929), pp. 335–36; J. J. Sederholm, "On the Use of the Term 'Deuteric,' " *Econ. Geol.*, Vol. XXIV (1929), pp. 868–71.

[3] J. J. Sederholm, "On Syantetic Minerals and Related Phenomena," *Bull. de la Comm. Geol. de Finlande, No. 48* (1916), pp. 1–148.

[4] R. J. Colony, "The Final Consolidation Phenomena in the Crystallization of Igneous Rocks," *Jour. Geol.*, Vol. XXXI (1923), pp. 169–78; "The Magnetite Iron Deposits of Southeastern New York," *New York State Mus. Bull. 249–50* (1923), pp. 70–71.

[5] J. L. Gillson, "Granodiorites of the Pend Oreille District, Northern Idaho," *Jour. Geol.*, Vol. XXXV (1927), pp. 1–30; "The Granite of Conway, New Hampshire, and Its Druse Minerals," *Amer. Min.* (1927), pp. 307–19.

duced in an open system at moderate temperatures. Some of the alterations in the granodiorite of the Pend Oreille district are very similar to those described in this paper. Sederholm[1] did not object to this proposed extended usage for the term "deuteric" but did object to Colony's proposal to use the term "deuterization" for the process of deuteric replacement. Sederholm's statement, in the discussion in *Economic Geology*, that "It may in many cases be difficult to decide whether the solutions have emanated from the nearest portions of the rock masses undergoing crystallization, or from magma still remaining liquid at greater depth," seems to the writer to imply that in all cases where it is possible to decide definitely that the solutions did come from magma at depth the term "deuteric" should not be used. Although it is probable that the solutions which produced the alterations described in this paper were derived in part from deep-seated magma, the fact that this cannot definitely be proved permits the alterations to be considered deuteric if the usage outlined above is followed.

But this leads to the question as to whether all reactions produced by emanations from the magma itself in rocks prior to their cooling to the temperature of the enclosing rocks are to be regarded as deuteric, or whether there should be a restricting lower limit to the term. If there is to be a lower limit, ought it lie between the low and moderate temperature stages of alteration, between the moderate and high temperature stages, or between results produced in open and closed systems? Would not the term "deuteric" be more useful if applied in the future only to those changes produced by reactions in a closed system? The writer prefers not to classify as "deuteric" the alterations described in this paper.

[1] J. J. Sederholm, "On Migmatites and Associated Pre-Cambrian Rocks of Southwestern Finland," *Bull. de la Comm. Geol. de Finlande, No. 77*, Part 2 (1926), p. 88; "On the use of the term 'deuteric,' " *Econ. Geol.*, Vol. XXIV (1929), p. 870.

ANHYDRITE AND ASSOCIATED INCLUSIONS IN THE PERMIAN LIMESTONES OF WEST TEXAS

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ABSTRACT

The non-clastic Permian sediments in west Texas consist of normal marine limestones, dolomites, and evaporites in ascending order. The dolomite, which appears in large part to be an altered marine limestone, contains numerous inclusions of anhydrite. This non-bedded anhydrite is divided into massive inclusions, phenocrysts, aggregates, vein and cavity fillings, and fossil replacements. The massive inclusions, phenocrysts, and most of the aggregates appear to be primary. The veins and fossil replacements are necessarily secondary.

INTRODUCTION

Anhydrite inclusions are common and widely distributed in the dolomitic phases of the Permian limestones in west Texas. The importance of these inclusions was recognized by Udden,[1] who microscopically examined the samples of the Swenson No. 1 Spur in Dickens County. He noted and figured several types of inclusions and discussed the occurrence in some detail. Developments of the last seventeen years have sustained most of his original deductions, but have added a number of additional problems and have furnished an immense amount of additional material.

Associations of dolomite and anhydrite similar to that in west Texas have been noted in many places, but opportunities to study the related stratigraphy and sedimentation in as much detail as is possible in the Permian basin of Texas are rare.

The Permian section in the west Texas basin consists of a series of desiccation deposits. The lower beds of normal marine limestone are overlain by fossiliferous and non-fossiliferous dolomites which in turn are followed by evaporites. The evaporites consist of anhydrite and halite with minor amounts of potassium and magnesium salts. The limestones and dolomites are apparently both organic and inorganic in origin. The evaporites are principally chemical precipi-

[1] J. A. Udden, "The Deep Boring at Spur," *Univ. of Tex. Bull. 363* (1914).

tates. The extensive interfingering of these deposits suggests interrupted cycles of deposition due either to differences in the rate of sea-water inflow, to the shifting of the barrier over which the unconcentrated waters entered the basin, or to changes in the direction of flow of the afferent currents. Baker[1] and Lloyd[2] have described the conditions under which the Permian deposits were formed.

The chemical and organic sediments grade laterally into clastics. In the center of the basin the clastics are represented by fine sandstones, shales, and bentonites. In the closing phases of deposition the clastics buried all the preceding deposits. Cartwright[3] has described this sequence in the upper, or known, portions of the basin area in considerable detail.

DESCRIPTION

True anhydrite inclusions are limited to the dolomitic phases of the series and no attempt is made here to cover the bedded anhydrite deposits of the evaporite column. The inclusions range in size from microscopic specks to great beds many feet in thickness. The larger bedded deposits, which are not discussed here, are probably lagoonal deposits formed under much the same conditions as the evaporites in the upper part of the section. The material here classed as anhydrite may include magnesite, anhydrite, or gypsum, all of which have been reported from this part of the section, and the rock called dolomite probably includes much magnesium limestone.

A brief description is given below of some of the more common types of non-bedded inclusions. The data have been derived by studying bit fragments, rough and polished sections of cores, thin sections, and insoluble residues prepared by dissolving the dolomite in weak acid.

MASSIVE INCLUSIONS

The masses of granular white anhydrite which occur, scattered through the entire dolomite section, are the most prominent of all

[1] Charles Laurence Baker, "Red Beds and Saline Residues of the Texas Permian," *Univ. of Tex. Bull. 2901* (1929).

[2] E. Russell Lloyd, "Reef Barriers and Saline Residues," *Bull. Amer. Assoc. Pet. Geol.* (1931).

[3] Lon D. Cartwright, Jr., "Transverse Section of Permian Basin," *Bull. Amer. Assoc. Pet. Geol.*, Vol. XIV (1930), pp. 969–81.

the anhydrite inclusions. They range in size from a fraction of an inch to a foot or more in diameter, and for this reason can be studied only in cores. The cores, which are seldom more than three or four inches in diameter, cannot furnish a complete picture of the larger masses which may thus occasionally be confused with bedded lenses. Smaller inclusions, however, are sometimes secured entire. They appear to occur both in definite zones and scattered irregularly through the section. It is possible that the zonal inclusions may grade laterally into bedded deposits. There is a tendency for the smaller masses to group themselves into clusters separated by thin walls of dolomite. A similar grouping of the larger masses may also occur.

The term "massive" is limited to those inclusions composed of granular anhydrite. In all other inclusions except the smallest isolated crystals, the incomplete fillings of open cavities, and the widest veins, the anhydrite occurs as coarse, dense, compact crystals. The granularity and loose cementation leave the anhydrite softer than the enclosing dolomite; this allows the surface to be etched by hydraulicking during rotary coring and gives the cores a false impression of great porosity.

The margins of the inclusions are either arcuate or lobate and the contacts of the anhydrite are usually sharp, but exceptions to the sharp contacts are often observed at the ends of embayments where the anhydrite and dolomite may intergrade. Veins of anhydrite sometimes grow out from the inclusions at these points and often connect with other massive inclusions. The contacts of the anhydrite and dolomite are, in many cases, marked by a thin band of insoluble black material containing dark shale, manganese, and minute pyrite crystals. Where the massive inclusions have grown together, stringers of this black material or of dolomite extend outward from the separating promontories and often have the appearance of being smeared out along partings in the anhydrite. Where two massive inclusions are tightly oppressed, the wall of insoluble residues alone is retained.

In a few cases the cavities occupied by these massive inclusions suggest the molds of large fossils. Usually, however, the shape is not so suggestive of the origin. Their common occurrence with known

porous horizons suggests that some masses fill original vugs or solution cavities in the dolomite. Many of the inclusions show evidence of growth at the expense of the surrounding dolomite. This is especially apparent when they occur in areas thickly sprinkled with disseminated anhydrite. Apparently here the scattered inclusions have congregated themselves into a solid mass which purified itself by recrystallization and the driving out of most of the intergranular dolomite which now forms dense walls around the inclusions. Some of the dolomite was occluded and occurs as isolated grains in the anhydrite. However, the wide distribution of the inclusions and the great mass of the anhydrite present in them can be best explained by the theory that the anhydrite and dolomite are contemporaneous deposits. The early formation of the anhydrite is further suggested in some of the argillaceous dolomites where the banding of the dolomite shows that the soft, shaly, lime muds flowed around the solid or semisolidified masses of anhydrite. Secondary changes as those due to pressure and recrystallization and the introduction of new material have only slightly affected most of the inclusions.

DISSEMINATED INCLUSIONS AND AGGREGATES

With the exception of the granular masses and wider veins, the anhydrite of the inclusions occurs as coarse, clear, and brown crystals. Both primary and secondary deposits of coarsely crystalline anhydrite are recognized. Primary anhydrite inclusions are scattered indiscriminately through the dense, granular, argillaceous, and sandy dolomites. The inclusions range from simple isolated grains to complex aggregates. There is a fairly complete gradation between, although the type of anhydrite depends to a considerable extent upon the nature of the associated dolomite. The coarsely crystalline inclusions are best studied in thin sections and insoluble residues, but a good idea of the distribution can often be secured from polished surfaces of cores. This is especially true in the denser portions of the dolomite where the anhydrite stands out as phenocrysts surrounded by a fine-grained matrix. Fortunately, in preparing insoluble residues, the dilute acid, used to dissolve the dolomite, attacks the anhydrite very slowly and the sharpness of the anhydrite outlines is retained after digestion.

Isolated inclusions are classed as granules or euhedral crystals depending upon the shape of the grain present. Small subcubical crystals are common, and short stout prisms, terminated by brachydomes, are occasionally encountered. Aggregates are formed by the union of these isolated grains into clusters. These clusters may take the form of bunched crystals and beads, platy masses, coarse and lacy networks, bladed rosettes and tube fillings. They can be divided into two classes. In the first, the anhydrite occurs between and around the dolomite grains; in the second, it fills solution cavities and wormholes in the rock.

The inclusions which fill interstitial spaces vary with the texture of the dolomite and with the changes in proportion of anhydrite and dolomite. In the simplest aggregates adjacent, isolated grains connect through the intergranular openings in the dolomite. At this stage, thin sections still suggest isolated inclusions forming a very minor constituent of the rock. In a similar way, the anhydrite fills part of the open spaces around the öolites and pellets which are so common in some parts of the dolomite section.

Under the microscope, adjacent grains of anhydrite, which are completely separated in the plain of the thin section, frequently show parallel extinction. Apparently they are all parts of a single large crystal which was forced to grow in this disjointed manner because of space limitations. As the percentage of anhydrite increases, more of the interstices are filled. The anhydrite inclusions gradually increase in size and begin to crowd between the grains of dolomite. With still greater proportions of anhydrite, isolated grains of dolomite and separated dolomite structures occur, surrounded by anhydrite. The anhydrite at this stage begins to develop crystal faces and frequently one large crystal will enclose numerous grains, pellets, öolites of dolomite. Pellets and öolites, although similar in shape, are referred to separately because they seem to be mutually exclusive. Many of the pellets have hollow cores filled with anhydrite. An example of this texture is shown in Figure 1. The anhydrite may also form several of the concentric shells of öolites. The enclosed anhydrite may be made up of numerous small grains or may form part of the larger surrounding crystals. On broken cores the anhydrite mixed with dolomite sometimes shows uniform cleavage faces

over areas as much as an inch in diameter. It does not, however, develop the euhedral outline characteristic of sand calcites and barites.

The final stage in anhydrite-dolomite mixtures is that in which granular öolitic and pellitic dolomite occurs, widely scattered in a ground mass of coarsely crystalline anhydrite. Rogers[1] has sug-

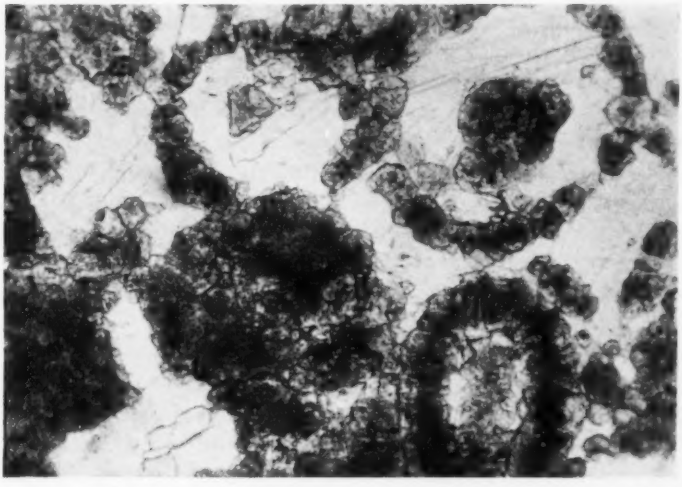

FIG. 1.—Photomicrograph × 90 diameters. Dense and hollow dolomite pellets filled and separated by white coarsely crystalline anhydrite.

gested that the powdery dolomite sprinkled through some of the larger anhydrite crystals represents a dolomite replacement.

Where the anhydrite is abundant enough to encircle and separate the dolomite structures, anhydrite sunbursts commonly develop. These include the radiating crystals and platy anhydrite aggregates and are so named because of their brilliant appearance when examined in thin sections with polarized light. Ideally, they should consist of perfect spheres of bladed crystals radiating outward from a common center. As found, however, the rosettes are neither regular nor complete. Because of space limitations, there is a tendency for adjacent sunbursts to interfere with each other's development and,

[1] Austin F. Rogers, *Personal Communication to Lon D. Cartwright, Jr.*

in many cases, the longer bladed crystals form radii for two or more sunbursts.

All stages in aggregate gradations can be shown in the insoluble residues. In these the anhydrite is preserved as dolocasts, very few of which preserve the imprint of rhombohedrons. This is easily explained by the fact that rhombohedrons are exceedingly rare in the Permian dolomites. Networks in the primitive aggregates are composed of rather disconnected curvilinear members which frequently show a triangular cross-section. At this stage the framework often crumbles from its own weight. When preserved in larger fragments, it resembles the lacy skeletons of some of the simpler radiolarians. As the proportion of anhydrite increases, the frame becomes more solid and more firmly welded and the fibers are sometimes interspersed with massive nodes. The coarser inclusions, which are usually most abundant in the dense dolomite, show somewhat similar gradations, but, since the single crystals are sometimes more than an inch in diameter, the aggregates are frequently very massive. These large anhydrite bodies are distinguished from the true massive inclusions by the coarseness of crystallization. In a few cases, however, the largest crystalline inclusions contain cores of massive anhydrite. Aggregates of the bead-like inclusions, which also belong in the coarser class, are frequently quite graceful in outline. As a rule, their true nature can be seen only after digestion, for on flat surfaces they appear as isolated phenocrysts. In the most advanced stages of anhydrite-dolomite mixtures, solution of the dolomite only slightly scores the anhydrite.

From the intimate association of coarsely crystalline anhydrite and dolomite it seems probable that the two are contemporaneous. The varying proportions ranging from scattered anhydrite inclusions in dolomite to isolated grains of dolomite in anhydrite are due to local differences in the concentration of the precipitating solutions. Strong evidences of contemporaneity are the anhydrite zoning of the öolites, the presence of phenocrysts in the dense dolomite which show no evidence of replacement, and the ubiquitous distribution of inclusions through some 3,000 feet of dolomite section. The coarseness of grain, when compared with known secondary deposits, suggests that most of the anhydrite has been recrystallized since deposition.

WORM TUBE FILLINGS

The simplest type of secondary deposit is that in which the anhydrite fills continuous tube-like openings in the dolomite. These inclusions, because of their size, are recognized only in the larger chunks and cores. Here they can be observed both on polished surfaces and in insoluble residues. The anhydrite rods, disclosed by solution, may be divided into several grades, the largest of which is less than 2 mm. in diameter. Most of the tubes in which the anhydrite is deposited are twisted and interwoven into vertical and horizontal loops although a few occur in semiparallel rows. Tubes of the same size are sometimes connected by branches. Tubes of different sizes may be connected but such connections have not been observed. However, tubes of all sizes may come in contact with each other and, where they do, the anhydrite fillings are cemented together by recrystallization. Additional unions, between the anhydrite rods in separate tubes, are furnished by interspersed inclusions of other types. Supplementary to the regular branching, numerous spindle-shaped caeci are developed. The anhydrite horns filling these holes may in turn branch.

Although the anhydrite forms a framework, the separate rods are seldom organized into a solid net, and the members fall apart when the supporting dolomite is removed. For this reason it is advisable to halt digestion while a core of dolomite still remains in the center of the mass, and even then there is considerable crumbling, for the rods show that some of the tubes were partially crushed before the introduction of the anhydrite. Nodular surfaces are common and some of the rods show faint longitudinal striations. These inclusions differ from the dolocasts in that they are not affected by the texture of the enclosing dolomite. On chance sections, however, they may easily be mistaken for phenocrysts.

Similar tubes, not filled with anhydrite, occur in many parts of the denser dolomite. They twist about in the rock and branch irregularly. It is sometimes possible to follow them completely through a core with a stiff bristle or other flexible probe. Irregularly spaced sections of these tubes are frequently filled with powdery crystalline gypsum. From their shape and continuity it seems probable that the tubes represent worm-borings which were cut through the compact but still soft dolomite muds. The anhydrite was apparently intro-

duced some time later in rock history. Where the tubes were crushed, the anhydrite rods show flattening, and, where there was insufficient calcium sulphate to fill the tubes completely, it was deposited at irregular intervals as powdery gypsum. Several other hypotheses have been advanced to explain the origin of these tubes. But from their lack of symmetry it seems improbable that they represent replacements of bryozoa or other elongate fossils.

VEIN ANHYDRITE

The anhydrite veins, which are widely scattered through the dolomite, form another group of secondary inclusions. The megascopic structure of the veins can be seen only in the cores. Thin sections furnish many additional data on the microscopic structure. There are great variations in the size and complexity of the vein groups. The smallest veins are microscopic. The largest one observed was a vertical vein almost an inch wide, cutting diagonally across a four-inch core for a distance of about fourteen inches. It is probable that much larger veins exist but so far none have been recognized. Veins up to a quarter of an inch wide are common, but the most prevalent type in the cores are those two or three inches long and about one-twentieth of an inch wide. The larger veins are usually filled with granular white anhydrite; whereas that in the smaller ones is dense, coarsely crystalline, and almost always darker than the enclosing dolomite.

From an examination of the cores and thin sections, it is apparent that the veins follow and fill cracks in the dolomite. They also follow the slickensided surfaces of joint faults and the irregular walls of stylolites. Smearing of the anhydrite along these planes suggests that some of the movement followed mineralization. In the denser dolomites the vein-fillings are continuous. In the granular dolomites the anhydrite frequently occurs as disconnected crystals or lense-shaped masses at the intersection of the joints. In thin sections alternating crescent-shaped lenses of anhydrite and thin layers of dolomite can be seen to form nodes at the angles of some of the smaller veins.

In most of the short disconnected veins the presence of anhydrite is the only indication of fracturing. In many cases, however, the

cracking or brecciation extends beyond the limits of the anhydrite fillings. Some of these fractures may have been developed for the first time in coring. Usually the veins branch and anastomose with the fractures which they follow. Carried far enough the stringers of anhydrite fade out and disappear around the edges of the vein groups. A typical vein group is illustrated in Figure 2. Some of

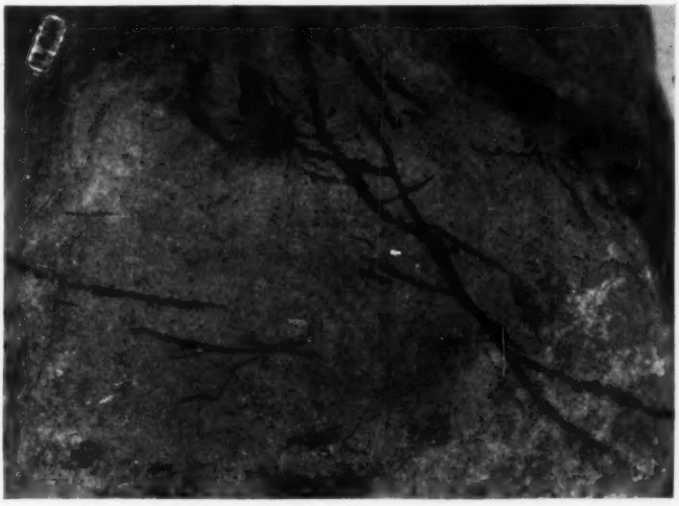

FIG. 2.—Anhydrite vein group in polished dolomite core. Natural size

the veins cross each other almost at right angles, and the offsets which are produced at such points suggest different ages of fracturing if not of mineralization. The presence of double veins along the same joint also suggests two periods of fracturing.

Veins, as a rule, cut across or branch out from other types of inclusions. Lateral displacements are noted between the intersected parts of these inclusions, and the displacements, in most cases, are as great in the small veins as in the larger ones. The vein anhydrite is almost always very distinct from that of the masses through which the veins pass. As seen in thin sections, the smaller veins in crossing inclusions may be represented as cracks with disconnected sec-

ondary crystals growing across them. This feature is especially noticeable in the large single crystal phenocrysts. Where several veins branch out from a massive inclusion, they radiate, as a rule, and suggest fillings in shrinkage cracks such as those observed in and around concretions. Radiating veins of this type are about an inch long. Somewhat larger veins have been noted connecting massive inclusions. These veins in the majority of cases are filled with granular anhydrite and indiscriminately parallel or cut diagonally across the bedding.

The grains of dolomite which line the walls of the veins may show crystal faces in contact with the anhydrite, while the attached ends are allotriomorphic. The same feature is observed in open cavities where the crystals were free to develop. Their presence along the veins suggests that open fractures existed before the introduction of the anhydrite. In veins without the secondary development of crystal faces, the fractures may never have opened or the conditions may not have been favorable for crystal growth.

Some of the dolomite grains along the walls are detached and lie free in the anhydrite. Others are only partially surrounded. Frequently incipient veinlets extend out into the dolomite for the thickness of three or four grains from the main vein wall. In many ways, these structures are similar to those developed in metallic veins. Apparently, the anhydrite, precipitated from cold waters, filled every possible crevice in the walls of the vein and the occasional splitting off of the more detached grains was caused by recrystallization.

FOSSIL CASTS

Anhydrite replacements of fossils and anhydrite fillings of fossil casts are probably the most interesting of all types of inclusions. Cores show that the non-dolomitic "Big Lime" is mainly composed of a mass of fossils. These include fusulinas and other kinds of foraminifera, brachiopods, bryozoa, algae, ostracods, crinoid stems, and other forms. Some of these fossils are retained in the dolomite, but in most cases part or all of the tests or shells were absorbed during dolomitization. Many of the molds thus formed have been partially or completely filled by anhydrite, and, in some cases, the anhydrite has replaced part or all of the fossil skeleton left after dolomitization.

The anhydrified fossils in these deposits occupy about the same

relation to the dolomite that silicified fossils do to normal limestones. The larger forms may be recognized in cores by their outlines. The characteristic cigar-shape of the fusulinas, which are very abundant, shows up beautifully in polished sections. Brachiopods and bryozoa can also be recognized in this way. Most of the micro-fossils can better be examined in thin sections or in insoluble residues. In the residues, all except the finer details of the external structure are preserved. The internal structure, when present, is best observed in polished sections. Thin sections do not present enough depth of field to recognize the various features and the insoluble residues frequently crumble. Unfortunately the anhydrite replacements of organisms are seldom complete enough for specific identifications.

OCCURRENCE

All types of anhydrite inclusions so far observed are limited to the dolomitic phases of the limestone. This association is strikingly brought out in cores of those wells which pass through alternating beds of limestone and dolomite. In fact, the inclusions are so characteristic of the dolomite that their presence alone indicates the nature of the rock. But, while the anhydrite is limited to the dolomite, about 10 per cent of the dolomite samples do not show any anhydrite. In the dolomite, the inclusions are not limited, or even dominant in any one type, but occur in the granular, dense, fossiliferous, oölitic, pure, argillaceous, and sandy phases. They are perhaps unduly abundant along sheer zones, but are also widely scattered throughout the massive and more solid portions of the rock. The association with shear zones may easily be explained on the theory that the presence of the anhydrite reduces the strength of the rock. Fossil replacements, of course, occur only in the fossiliferous dolomite and veins in that part of the rock which has been fractured. Other normal types are more or less evenly distributed from the top to the bottom of the dolomite, which in some places is as much as 3,000 feet thick. Structurally, however, the inclusions seem to be more abundant in the depositional lows than on the highs.

BORDER PHASES

Transition zones occur along the margins of many of the massive anhydrite inclusions. These border phases may be divided into

several groups. In one, there are alternating bands or halos of dolomite and anhydrite paralleling the face of the inclusion. Single bands of anhydrite outside the inclusions are common, two bands separated by dolomite are rare, and three bands are seldom observed. Sometimes the anhydrite in front of the inclusions does not occur in bands but as concentrations of isolated crystals. A variation which is frequently associated with the banded borders is the occurrence of one or more zones of isolated dolomite grains or rhombs in the anhydrite. When the bands between the layers of anhydrite are partially or wholly composed of insoluble residues, this type grades into the next.

In the second type, there is a segregation of insoluble material at the edges of the inclusions. Where large inclusions have grown together, the bands mark the original contacts. This type of border is especially common in impure dolomites and in those parts of the rock where there are many finely disseminated inclusions of anhydrite. The material of the bands is composed of shale frequently associated with considerable finely crystalline pyrite and occasionally with thin lenses of gypsum. In some cases the border material forms a turbid gradation zone of microscopic dust-like inclusions rather than a sharp band and on a few borders the segregated material consists of almost pure dolomite.

The third type is marked by the development of coarsely crystalline, secondary anhydrite around a granular core. This secondary material frequently extends out in radiating veins which resemble shrinkage cracks. The secondary material is usually much darker than the original mass which it surrounds. The border phases, formed of material other than anhydrite, are discussed under the next heading.

ASSOCIATED MINERALS

The minerals which line the cavities containing anhydrite or which occur floating free in the inclusions must necessarily be discussed with the anhydrite. Quartz, pyrite, and dolomite are the most important associated minerals.

QUARTZ

Quartz and anhydrite occur in a number of combinations in the massive inclusions. That in which the quartz forms geode-like linings of the anhydrite-filled cavities is probably the most common.

Usually these anhydrite-filled quartz geodes are characterized by a botryoidal outer shell of banded milky quartz or chalcedony. This is lined on the inside by one or more rows of short, free-ended quartz crystals capped by blunt pyramids which penetrate the central mass of anhydrite. The shape of the quartz coating depends entirely upon the shape of the inclusion which it surrounds. Sometimes the geodal development is not complete but is represented by groups of crystals or lenses of chalcedony scattered along the walls of the inclusion. Commonly, the geodes are accompanied by the development of isolated euhedral crystals and rosettes floating free in the anhydrite. Masses of this sort occur in some of the inclusions which do not have geodal borders.

PYRITE

Pyrite, usually as cubical crystals, is commonly associated with the anhydrite inclusions. Unlike the quartz, it occurs with all types of inclusions. It frequently forms a felt of crystals around or partially around the borders. These felty layers are usually thin, although locally they thicken and tubercles of pyrite extend out into the anhydrite. Associations of this sort were recently described and pictured in a report on the Hendrick Pool in Winkler County.[1] Pyrite may also accumulate along sheer zones or cracks which cross the inclusions. In places these crack fillings may become concentrated enough to be classed as veins. More commonly, however, the pyrite occurs as isolated cubes either along the margins or scattered through the anhydrite. On polished surfaces sparkling pyrite cubes can often be seen completely enclosed in anhydrite.

It seems that the anhydrite inclusions in certain zones of the dolomite carry more pyrite than other zones. The occurrence of pyrite with the anhydrite is interesting, but not especially diagnostic, because very similar pyrite deposits occur scattered through the enclosing dolomite.

DOLOMITE

The dolomite is the most important mineral associated with the anhydrite because it alone contains the inclusions. Microscopic dolomite rhombohedrons also form along some of the vein walls and around many of the smaller inclusions. Similar crystalline linings are common in most of the unfilled cavities. Powdery dolomite is

[1] A. L. Ackers, R. DeChicchis, and R. H. Smith, "Hendrick Field," *Bull. Amer. Assoc. Pet. Geol.*, Vol. XIV (1930), pp. 923–45.

occluded in many of the phenocrysts and unsupported crystals, and grains of dolomite are common along the margins of many of the inclusions. In the aggregate inclusions the shape of the cavity quite often determines the shape of the inclusion. Rogers[1] suggests that the isolated dolomite crystals in the anhydrite may represent replacements. It seems more probable, however, that they are detached portions of the surrounding mass.

CALCITE AND SULPHUR

Calcite and sulphur are common constituents in some parts of the dolomite. Calcite, however, has never been observed in contact with anhydrite or even in close proximity to it. There is no apparent reason why the two should not occur, because calcite is very commonly associated with the anhydrite of the lower Castile in the Delaware basin. Sulphur crystals are frequently intergrown with the coarsely crystalline anhydrite inclusions in some parts of the dolomite. This seems to be a normal relation with the crystals of sulphur-filling spaces that would otherwise be filled by anhydrite. The contrast, in these places, of white and bright yellow is very striking. The absence of sulphur in the oil-saturated inclusions is strong evidence that sulphur is not a product of hydrocarbon reduction of anhydrite.

ORIGIN OF THE ANHYDRITE

In the preceding discussion, the probable origin of each type of inclusion follows the description. It is evident from observation that no one theory is capable of explaining all the types and varieties of inclusions. There are three plausible theories that may be advanced to explain the presence of the anhydrite. From their very constant association it seems probable that the anhydrite is closely tied up with the origin of the dolomite.

If we accept the theory that dolomite is formed beneath the sea by a replacement of part of a limestone by magnesium sulphate, it is possible to derive the following equations:

$$MgSO_4 + CaCO_3 \rightarrow MgCO_3 + CaSO_4$$

$$MgCO_3 + CaCO_3 \rightarrow MgCa(CO_3)_2$$

[1] A. F. Rogers, *op. cit.*

In this case the two end products are anhydrite and dolomite and the origin of the two is explained. If there was not enough $MgSO_4$ to complete the reaction, some calcite would be left in the limestone and, if there was an excess, magnesite might be formed. Both calcite and magnesite occur in the Permian beds of west Texas.

Unfortunately, we are not certain that dolomite is formed in this way, and the common absence of anhydrite in the dolomites elsewhere suggest a modification of this theory. It is quite evident that all of the anhydrite in west Texas is not a by-product of dolomitization. The big anhydrite series in the Upper Permian is undoubtedly an evaporation product. At the northern or inner end of the basin in Kansas the evaporites extend downward almost to the base of the Permian. To the south these evaporites interfinger with the dolomite which in turn grades into limestone. This gradation of contemporaneous deposits suggests that the anhydrite inclusions throughout the dolomite are primary concentration deposits or deposits from connate waters.

The presence of free sulphur, sulphate waters, and sulphuric acid in the "lime" suggests that the acid reacting with the calcium of the dolomite may have produced some of the anhydrite. Anhydrite resulting from the chemical alteration of dolomite should show substantial differences in character from deposits of other types. In the first place, the insoluble impurities in the dolomite would have a tendency to segregate as bands along the margins of the inclusions. Irregularities of shape similar to those found in replacement deposits of metallic ores should also occur. Both of these features are common in the anhydrite inclusions in west Texas. This method of origin may explain most of the anhydrite in the replacement deposits. Some of the secondary growth, however, may be due to recrystallization. It is probable that the anhydrite of the inclusions is due in part to all three of the above processes.

THE MECHANICS OF THE PLAINS-TYPE FOLDS OF THE MID-CONTINENT AREA

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ABSTRACT

The anticlines and domes of the Mid-Continent area appear to constitute a distinct type of structure, with certain definite characteristics. None of the previously published theories regarding the mechanics of these folds offers an adequate explanation of these features. These characteristic features are presented by illustrations of typical folds.

The characteristic features of these folds all suggest vertically acting forces rather than horizontal compression, and an analysis of the stresses developed in the overlying sediments by vertical displacement, due to movement along an old fault plane in the basement rocks, indicates that that hypothesis offers a satisfactory explanation of the type of folding developed, and of the normal faulting in connection with the folding.

INTRODUCTION

The numerous anticlines and domes in the oil-producing portion of the Great Plains area of the United States have been studied in great detail, both at the surface and in their subsurface aspects, because of their economic importance. But with all the abundance of data thus made available, no critical study of the mechanics of these structural features has ever been published.

The classic studies of the mechanics of folding have been largely based on the evidence available in areas of intense folding, such as the Appalachian Mountain region. That evidence suggested lateral compression of the strata as the dominant factor in the development of folding. Because of its widespread acceptance in the literature, many geologists have come to regard horizontal compression as responsible for practically all folding. There are, however, some exceptions to be noted. Powers[1] called attention to the presence of "buried hills" under many productive anticlines, and a number of writers have attempted to account for the anticlines in the overlying rocks solely on the basis of differential compaction over these buried hills. Fath[2] has postulated lateral displacement on opposite sides of a

[1] Sidney Powers "Reflected Buried Hills and Their Importance in Petroleum Geology," *Econ. Geol.*, Vol. XVII, No. 4 (1922), pp. 233–59.

[2] A. E. Fath, "The Origin of the Faults, Anticlines, and Buried 'Granite Ridge' of the Northern Part of the Mid-Continent Oil and Gas Field," *U.S.G.S. Prof. Paper 128.*

series of master faults in the basement rocks to account for most of the structural features of the Mid-Continent area.

CHARACTERISTICS OF TYPE FOLDS

It is believed that these anticlines and domes constitute a distinct structural type possessing certain characteristic features. Neither lateral compression nor differential compaction appears to afford an adequate explanation of these features. It will be the pur-

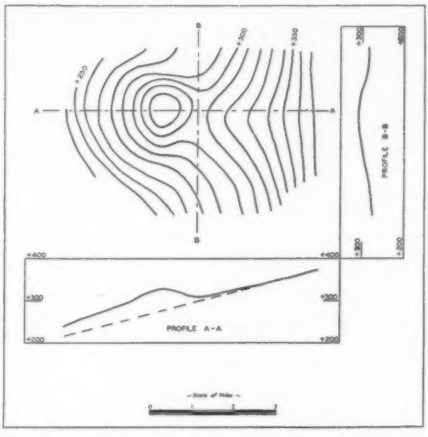

FIG. 1.—Structure of a typical small dome in northern Oklahoma

pose of this paper to consider the distinguishing features of these folds and to attempt to interpret the mechanics of their creation. At the outset it seems advisable to make a distinction between the folding and faulting of the sedimentary rocks concerning which we have an abundance of data, and the structure of the underlying basement rocks which must remain largely a matter of speculation.

The first outstanding characteristic of the Plains-type fold is that the net result of the folding is always a local uplift, without any corresponding depression. That is, there are virtually no true synclines, in the sense of downwarped folds, but only anticlines and domes raised above the normal monocline. This fact is illustrated by Figure 1, which shows a structure map and profiles of a small dome.

It will be noted that no part of the profile of the key bed extends below the normal dip line projected across it. It will also be observed that what we are accustomed to think of as a syncline on the east of the dome is in reality a slightly elevated saddle which is anticlinal in north-south cross-section. While the illustration used represents the structure of a shallow bed, as defined by core drilling, the statement that there is no corresponding downwarp holds true for the oldest sediments involved.

Another characteristic feature of these folds, which has been pointed out so often that it needs no elaboration here, is that they become more pronounced with increased depth. And as a corollary statement, there is a definite thinning of the strata over the crests of the folds. This thinning is often so pronounced that a fairly accurate picture of the structure of a producing anticline can be obtained by contouring the interval between a shallow and a deep marker horizon.

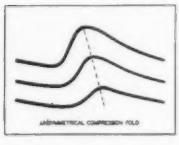

FIG. 2.—Showing axis inclined toward steeper limb, and increased intervals along axis, in a compression fold.

A third distinctive feature lies in the fact that while these folds are usually unsymmetrical, with one limb much steeper than the other, they do not possess the characteristics of the unsymmetrical compression fold, in which the axis is inclined toward the steeper limb. On the contrary, such shifting of the axis as occurs is in the reverse direction. Figure 2 shows the inclination of the axis in an unsymmetrical compression fold, while Figure 3 shows the opposite inclination as it occurs in the Tonkawa anticline.

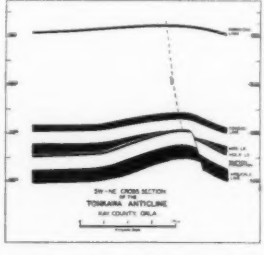

FIG. 3.—Showing axis of fold inclined away from limb with steeper dip.

The fourth generalization regarding these Plains-type folds is that normal faulting is commonly associated with the folding, particularly in the pre-Pennsylvanian rocks as at Tonkawa (Fig. 3), although it may also be present in the Pennsylvanian as at Oklahoma City (Fig. 4), or may involve the entire Pennsylvanian and Permian sections as

in the Retta field (Fig. 5). But thrust faulting of the sedimentary rocks in the type folds is unknown. This is not to be inter-

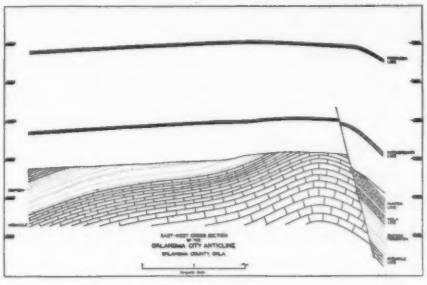

FIG. 4

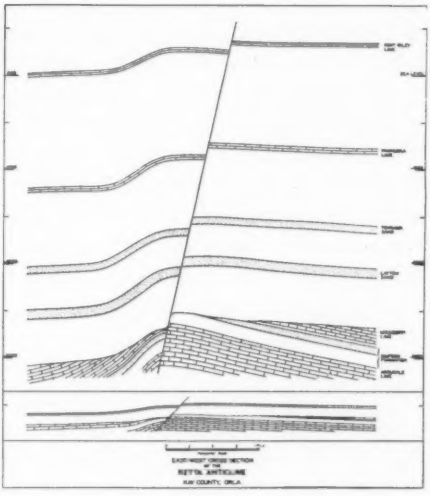

FIG. 5

FIGS. 4 AND 5.—Fig. 4: Vertical scale exaggerated to show relation of folding in Permian and Pennsylvanian to pre-Pennsylvanian structure. Fig. 5: Lower part of section to same vertical and horizontal scales to show true dips and true angle of faulting. Note that axis of folding is practically vertical but fault plane dips at an angle of approximately 45°.

preted as meaning that thrust faulting is nowhere present in the Mid-Continent area, as there are a number of known instances in

the Greater Seminole field,[1] and there is a possibility that thrust faulting is present in the older rocks in the Voshell, Kansas, anticline. But the Seminole structures are not to be classed as true Plains-type folds, so for classification purposes we may say that folds which involve thrust faulting of the sedimentaries do not come within the meaning of the term. Normal faulting, however, is commonly a conspicuous feature of the structure of the pre-Pennsylvanian rocks.

MECHANICAL CLASSIFICATION OF FOLDS

Before attempting to analyze these folds from a mechanical standpoint, it seems advisable to consider briefly the classification of folds on that basis. Willis[2] classifies folds, according to the stresses responsible for their formation, as competent and incompetent folds.

Competent folding is defined as "that folding which is produced by compression in the direction of the undisturbed stratification, and which is conditioned by the requirement that a rising arch shall lift the load, or a sinking syncline shall displace the underlying material." Under these conditions a stratum behaves like a column or a strut under compression, and, if sufficient stress is applied, will fail either by shearing or buckling. The mode of failure will be determined by the slenderness ratio of the stratum and the degree to which it is confined by the weight of the overlying sediments. Thus, a short thick strut will tend to fail by shearing, whereas a long slender strut will tend to fail by bending or buckling, if unconfined. But if the slender strut is sufficiently confined, it may also fail by shearing. It is obvious that shearing failures resulting from horizontal compression of strata will constitute thrust faults.

The following conditions are necessary in order for a competent anticline to develop: (1) a large compressive stress acting approximately parallel to the bedding planes; (2) a slight initial flexure to permit the development of a component of uplift; (3) a stratum or a

[1] Deep Rock Oil Company's No. 2 Douglas located in Sec. 30, 8 N., 8 E., and Sorry-Schwartz No. 1 Bruner in Sec. 26, 10 N., 5 E., both furnished evidence of thrust faulting in the pre-Pennsylvanian rocks. These wells probably represent the most clean-cut and unmistakable instances of repetition of section of the numerous cases reported in this area.

[2] Bailey Willis, *Geologic Structures* (1st ed.), pp. 148–60.

series of strata having sufficient strength to form an arch capable of lifting the load imposed by its own weight and that of any incompetent overlying beds.

From their method of formation, it will be apparent that competent folds will tend to develop as broad arches rather than narrow folds. Competent folds are further characterized by thinning of the strata on the limbs, and a corresponding thickening on the axis.

Incompetent folding is defined as that folding resulting from "a deflecting pressure which is initially directed approximately at right angles to the strata when they are in a horizontal or gently inclined position." Such folds may be regional in extent or relatively long and very narrow. They necessarily involve either subsidence or uplift. The strata involved in incompetent folding are passive, in contrast to the strata of a competent fold, which actually lift the load. By definition, folds formed as a result of intrusions, such as lacolithic domes, and domes or anticlines formed by the intrusion of salt masses, and all folds resulting directly from readjustment in the underlying basement rocks would be classed as incompetent.

If there is renewed movement on an old fault plane in the crystalline rocks, after sedimentary rocks have been deposited across the old fault trace, it is clear that this movement will produce an unsymmetrical anticline in the sedimentary rocks. But such a fold will not have the same characteristics as an unsymmetrical compression fold, as the force applied to the sediments is primarily one of relative uplift.

STRESSES DEVELOPED IN INCOMPETENT FOLDING

The sedimentary beds over such a fold will be subjected to horizontal tensile and compressive stresses acting parallel to the bedding planes, vertical compression, and shearing stresses acting across the bedding planes. If the movement is great enough and the weight of overburden sufficient, these shearing stresses may exceed the shearing strength of the lowermost sedimentary beds, in which case shear fractures will be formed, starting at the edge of the uplifted portion of the crystalline rocks and passing upward at an angle approaching 45 deg. with the vertical and inclined away from the steeper limb of the anticline. In geological terminology, such fractures are normal

faults. Incompetent folding of the type described above may be produced in the sedimentary rocks by a high-angle thrust fault in the underlying crystalline rocks. In other words, compressive stresses in the basement rocks do not necessarily result in the development of competent folds in the sedimentary rocks.

The strata involved in incompetent folding are analogous to the uniformly loaded beams of structural engineering, and the stresses developed can be analyzed by the methods of that profession. These methods will be applied in the discussion that follows.
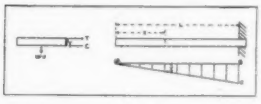
FIG. 6.—Showing method of analyzing stresses in a cantilever beam, and the shear diagram for uniformly distributed load.

Figure 6 shows a cantilever beam subjected to a uniform load of (w) pounds per foot. The stresses developed at any vertical section of the beam are determined by assuming the beam to be cut through at that section, and computing the forces that would have to be applied to the cut end of the beam to the left of that section to maintain it in equilibrium. Now if we assume that the unit weight (w) includes the weight of the beam itself; and if we cut through the beam at a distance (x) from the free end, it will be evident that an upward force (v), equal to (wx) the total weight of that portion of the beam and its load on the left of the section, will have to be applied in order that the summation of the vertical forces acting upon the body may equal zero, which is the first requirement for equilibrium. This vertical force represents the shear at that section.

If we compute the shear for a number of different sections along the beam, and represent these values by vertical lines whose length is proportional to the shear at the particular section represented, we get the shear diagram ABC on which AB represents the length of the beam and AC is a line joining the ends of the vertical lines representing the values of the shearing stresses. It will be noted that the shearing stress attains its maximum value at the edge of the support.

But, while the vertical forces acting upon the free segment of the beam have been balanced by the application of the force (v), that segment is not in equilibrium, because the weight of the segment wx

acts at a distance of $\frac{1}{2}x$ from the left end; whereas the balancing vertical force (v) is applied at the cut section, at the distance x from the left end. The segment is, therefore, acted upon by a couple tending to rotate it in a counter clockwise direction. This couple must be opposed by another couple which can be represented by the tensile force (T) applied to the top of the cut section and the compressive force (C) applied at the bottom.

Since (T) and (C) are the only horizontal forces acting upon the segment, it follows that they must be equal for the segment to be in equilibrium. Further the moment of the couple (T, C) must equal the moment of the couple (v, wx). Then the three requirements for equilibrium of the free segment have been satisfied; i.e. (1) the summation of the vertical forces equals zero; (2) the summation of the horizontal forces equals zero; (3) the summation of the moments equals zero.

When the shear or moment at a section of a beam is referred to, the internal shear or moment is meant. But to determine the amounts of these internal stresses it is necessary to compute them in terms of the external stresses which would have to be applied to produce equilibrium if the beam were cut through at that section. This is the fundamental method of analyzing the stresses in beams. It is directly applicable to simple beams, cantilever beams, and overhanging beams. While the total shear and the total moment may be determined by the above methods, the unit stresses are the factors that determine the ability of the beam to sustain its load. These unit stresses are usually expressed in pounds per square inch, but may be in any units desired.

The unit shear at any section is obtained by dividing the total shear at the section by the area of the section. Since the maximum total shear in a cantilever beam occurs at the edge of the support, if the beam is of uniform cross-section, the maximum unit shear occurs at the same place and is equal to the total load divided by the area of the cross-section.

The unit tensile and compressive stresses at any section of a beam, subject to bending moment, do not have a constant value for all fibers of the beam, but vary from zero at the neutral axis to maxima in the outermost fibers. The situation is illustrated diagrammatically

in Figure 7 in which the fibers above the neutral axis are in tension, while those below it are in compression. Since the summation of the moments of these internal stresses must balance the external moment,

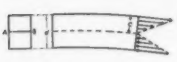

FIG. 7.—Showing distribution of the tensile and compressive stresses at a section of a beam subjected to bending moment.

$$M = \frac{SI}{c} \text{ or } S = M \div \frac{I}{c}$$

in which M equals the external moment and $\frac{SI}{c}$ is the summation of the internal moments,[1] S being the unit stress in the outer fibers, I the moment of inertia of the section about line A B, and c the distance from the neutral axis to the outer fiber. Then to determine the maximum unit tensile or compressive stresses that occur in a beam, it is necessary to locate the section at which the maximum moment occurs, and then compute the unit stress in the outer fibers at that section.

For a cantilever beam with a uniform load the maximum moment occurs at the fixed end and is equal to the entire load (W) multiplied by $\frac{1}{2}$ of the length of the beam, thus:

$$M = \frac{WL}{2}$$

For a solid rectangular cross-section, the section modulus $\frac{I}{c} = \frac{bd^2}{6}$. Therefore, to determine the maximum unit tensile or compressive stresses for that particular type of cantilever beam, the equation

$$S = M \div \frac{I}{c}$$

becomes

$$S = \frac{WL}{2} \div \frac{bd^2}{6}$$

If the stress is to be expressed in pounds per square inch, all dimensions must be expressed in inches. If dimensions are expressed in feet, unit stresses will be in pounds per square foot.

[1] A. P. Poorman, *Strength of Materials*, pp. 90 and 100.

It is impossible to compute the actual stresses in a particular fold because the loading cannot be known. But it is possible to set up a hypothetical case in which the stresses can be computed, and from it obtain a fair idea of what has happened in the actual folds. Figure 8 shows a bed of limestone 1,000 feet thick which has been uplifted at A by a displacement of the underlying crystalline rocks along an old fault plane (F). Under these conditions the portion AB of the limestone bed is in effect a cantilever beam under the uniformly distributed load of its own weight. The known factors are:

FIG. 8

The unit weight of limestone = 160 lb. per cu. ft.
The ultimate strength of limestone, in compression is
2,500 lb. per sq. in. or 360,000 lb. per sq. ft.
in shear is
1,500 lb. per sq. in. or 216,000 lb. per sq. ft.
in tension is
150 lb. per sq. in. or 21,600 lb. per sq. ft.

Since the dimensions of the beam are large it will simplify the computations to use the pounds per square foot values of the ultimate strength figures, in order to avoid excessively large figures. Considering a vertical segment of the bed, the unit weight (w) per foot of length is $160 \times bd$. Since the rock is weakest in tension, the tensile stresses will be considered first.

For a uniformly loaded cantilever of solid rectangular cross-section, the equation

$$S = M \div \frac{I}{c}$$

becomes

$$S = \frac{WL}{2} \div \frac{bd}{6} = \frac{3WL}{bd^2}.$$

But

$$W = 160\ bdL$$

therefore

$$S = \frac{3 \times 160 \times bdL^2}{bd^2} \text{ or } S = \frac{3 \times 160 \times L^2}{d}.$$

Since in this case $d = 1{,}000$ and the maximum possible value for S is 21,600 we may write the equation

$$21{,}600 = \frac{3 \times 160 \times L^2}{1{,}000}$$

or

$$L^2 = 45{,}000$$

and

$$L = 212 .$$

From which it follows that the unsupported length AB cannot exceed 212 feet. When that length is reached, further displacement will cause failure through the development of tension fractures or joint cracks in the upper surface of the beam, above the edge of the support. This is important as it indicates that the unsupported limb of an incompetent fold of this type must be very short.

The maximum unit vertical shearing stress for this limiting length of 212 feet in the above case is:

$$\frac{wL}{bd} = \frac{160\ bdL}{bd} = 160 \times 212 = 33{,}920$$

This figure is small in comparison with the ultimate strength in shear of the limestone, so it is evident that the limiting length determined by the tensile stresses is the true limiting length of the beam in this case.

If the depth of the beam is increased, its strength in respect to the tensile stresses will be increased since S is inversely proportional to d^2. The limiting length of the unsupported portion will, therefore, be increased and consequently the maximum unit vertical shearing stress will be increased. Beyond a certain value of d, the vertical shearing stresses would determine the maximum possible length of the beam. Hence, the beam would fail by shearing vertically before the maximum tensile stresses had reached the ultimate tensile strength of the limestone. But it can be shown, that for this situation to exist, d, or the thickness of the limestone, would have to exceed 40,500 feet. Consequently this situation never occurs in the group of folds which are being considered.

Since the maximum horizontal compressive stresses equal the

maximum tensile stresses, and the material is much stronger in compression, they need not be considered.

At this point the analogy with a structural beam ceases because the comparatively great thickness of sedimentary rocks introduce vertical compressive stresses due to the weight of the overlying portions of the bed or beds, which are an important factor in the mechanics of incompetent folding.

Considering a one-foot cube in the base of the limestone bed, before any displacement has occurred, it is evident that this cube will be subjected to a vertical compressive stress equal to $160 \times d$.

When a bar is subjected to a direct tensile or compressive stress, shearing stresses are induced on planes inclined at an angle with the direction of the applied forces. These induced shearing stresses attain a maximum unit intensity equal to one-half that of the direct stress on planes inclined at an angle of 45 deg. with the plane of the cross-section. This is illustrated in Figure 9 in which MN is a bar subjected to the direct compressive forces P, P. If the part of the bar on the left of the diagonal section AB is considered as a free body, the force P at the diagonal section may be resolved into two components, a compressive force C, normal to the surface, and a shearing force S, parallel to the surface.

FIG. 9.—Diagramming the development of induced shearing stresses along diagonal sections, as a result of direct compression.

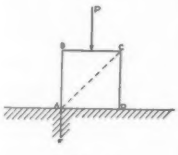

FIG. 10

In Figure 10, $ABCD$ represents a one-foot cube in the base of a limestone bed resting directly upon crystalline rocks and located just to the right of a fault plane in those rocks. Assuming that no displacement has taken place since the deposition of the limestone, the cube is subject to a vertical compressive pressure P due to the weight of the overlying rocks. Along the diagonal plane AC there is an induced unit shearing stress equal to $\frac{1}{2}$ P.

Since $P = 160 \times d$

if $\frac{1}{2} P = 216{,}000$, the ultimate strength of limestone in shear;

then $P = 432{,}000 = 160\ d$

and $d = 2{,}700$.

This means that limestone, the strongest of the sedimentary rocks, is potentially sheared by the pressure of the overlying rocks when their thickness exceeds 2,700 feet. Hence, under these conditions, if all the material to the left of AB were cut away, a shearing fracture would be initiated at A and would extend diagonally upward along the plane AC.

The rock is only potentially sheared, however, so long as no displacement occurs along the fault plane F. But if such displacement does occur, the situation is different from that developed by cutting away the material to the left of AB, in that the vertical pressure P is doubled due to the fact that the beds to the right of AB must carry the load of the unsupported beds to the left of that section. It follows that limestone is subject to diagonal shear under static load conditions when the thickness of the overlying rocks exceeds 1,350 feet.

The actual depth must be somewhat greater than this figure since there is an opposing diagonal shear induced along AC by the horizontal compressive stresses in the base of the beam. But unless the strata involved are also subjected to horizontal compression, the value of this opposing shear cannot exceed 10,800 pounds per square foot, which stress would be balanced by an additional 135 feet in depth. Faults originating in this manner will tend to die out upward, since the vertical pressure, and consequently the induced diagonal shear, decreases as it ascends the section.

Mechanically there is no difference between the so-called normal faults of incompetent folds, and the thrust faults of competent folding. Both are failures resulting from diagonal shearing stresses, induced by direct compression. The only difference lies in the fact that the compression is applied horizontally in one case, and vertically in the other. It is clearly incorrect to call such normal faults tension faults, since the forces normal to the fault plane are compressive rather than tensile, and there is no tendency for the opposite faces to pull apart and create an open fissure.

In all the preceding discussions the stresses have been computed for conditions of static, or very gradually applied load, since these represent the minimum possible stresses. Under conditions of impact, or suddenly applied loads, the unit stresses developed would approach values twice as great as those computed.

Innumerable variations from the values established in these hypothetical cases are possible. Weaker beds will fail under smaller loads. Any degree of horizontal compression existing in the strata involved will oppose both the tensile stresses and the diagonal shearing stresses due to uplift, and will consequently increase the thickness of strata that can be lifted without failure. But such horizontal compressive stresses will not make the fold a competent one so long as they do not actually produce the fold.

A study of the folds of the Plains type indicates that they belong to the class of incompetent folds. The structure of the pre-Pennsylvanian rocks, which consist predominantly of hard limestones or dolomites, is commonly an uplifted and tilted segment of strata, flexed slightly along a very narrow crest and sheared by a normal fault or faults on the steeper limb. This suggests an upthrust of a rotational character in the underlying crystalline rocks. But it is not necessary to postulate thrust in the crystalline rocks, since their displacement may also take place along normal faults, or vertical faults developed in the zone of fracture by still deeper forces of uplift.

STRUCTURAL HISTORY OF FOLDS

The known structural history of these folds includes a succession of movements along these postulated faults in the basement rocks. These lines of weakness are probably extremely old. While the outstanding displacements in the Mid-Continent area occurred at the close of Mississippian time, there is evidence of earlier movements, particularly at the close of Hunton time, and later movements at intervals throughout Pennsylvanian and Permian time.

The post-Hunton, pre-Mississippian movements for the most part resulted only in a very slight upwarping of the sedimentary rocks. The post-Mississippian pre-Pennsylvanian movements resulted in pronounced uplift and much normal faulting. Prolonged erosion immediately following greatly modified the resulting topographic features by truncating the tilted beds, and reducing the height of the fault scarps. But because of the resistant nature of the rocks involved, the structural highs persisted as hills, or topographic highs, throughout this period of erosion. The earliest Pennsylvanian beds were, therefore, laid down over these hills, which ac-

counts, in part, for the shorter intervals over the crests of the folds. Since the slopes of most of these hills were at rather low angles, it is not improbable that these beds were deposited with some degree of initial dip.

Further displacement of the basement rocks in Pennsylvanian and Permian time uplifted the resistant hills of pre-Pennsylvanian rocks. They in turn uplifted the overlying beds. The stresses developed in the overlying beds were the same as in the case previously considered. But the large percentage of shale in the section tended to permit some of these stresses to be relieved by a thinning of the strata over the crest of the structure and a corresponding thickening on the flanks. In the course of such adjustments the beds supported by the pre-Pennsylvanian hill necessarily assumed the form of an anticline or dome, the shape being determined by the configuration of the underlying core. But when the displacement was carried far enough, the Pennsylvanian and Permian strata also failed by shearing with the consequent development of normal faults.

The shifting of the axis of these folds away from the steeper limb as it ascends the section is due first of all to the fact that the fold in the younger beds conforms to the shape of the pre-Pennsylvanian, and secondarily, to the fact that the greatest thinning of the shales is normally vertically above the pre-Pennsylvanian fault scarp even though it is not at the crest of the structure. Depositional dips may also play some part in determining the position of this axis.

CONCLUSIONS

A critical examination of the type of folds designated as Plains-type structures shows that they do not possess any of the characteristics which are accepted as the criteria for the recognition of competent or compression folds. On the other hand, their characteristic features are exactly those which would be developed as a result of incompetent folding of the type due to relative uplift along an old fault plane in the basement rocks.

The normal faulting associated with the folds is interpreted as a failure due to diagonal shearing stresses, induced by vertical compression, which becomes effective when the opposing stresses are relieved in the unsupported limb of the fold. Normal faulting of this

sort and thrust faulting are seen to be identical failures from a mechanical standpoint, the only difference being in whether the force is applied vertically or horizontally, from which it follows that thrust faulting is indicative of horizontal compression, and that this type of normal faulting is indicative of relative uplift. In the absence of any evidence of thrust in an area, a geologist should be wary of attributing folds within it to horizontal compression.

ACKNOWLEDGMENTS

The writer is indebted to Sidney Powers for detailed criticisms of the manuscript, to B. B. Weatherby for checking all computations and for valuable suggestions regarding the form of presentation of some of the mathematical argument, to E. H. Griswold for assistance in checking computations, and to L. F. Athy for inspection of the manuscript for possible errors in mechanics.

ERRATIC BOULDERS IN SEWELL COAL OF WEST VIRGINIA

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ABSTRACT

The presence of erratics in coal has been known for several years, but to the writer's knowledge the present discovery in the Sewell coal of West Virginia (Greenbrier County) represents the largest, as well as the greatest number and variety yet reported. The present paper gives references to previous discoveries, as well as an account of the size, shape, and position in the coal seam, character of boulders, their probable source, and possible agents of transportation of the boulders at this locality.

INTRODUCTION

During the summer of 1929, while in the office of the Gauley Coal Land Company, the writer noticed a fragment of a vein-quartz boulder coated with coal. Upon inquiry, Mr. B. H. Higginbotham, resident engineer for this company, stated that several such rocks had been encountered in the mining operations at Quinwood. A visit to the several mines operating in this county resulted in locating three mines where such boulders had been encountered in the coal: those of the New River and Pocahontas Consolidated Coal Company at Leslie, the Margarette Coal Company at Marfrance, and the Leckie Coal Company at Anjean. Although the majority of the boulders were found in adjoining entries of the Margarette and Leslie mines, the presence of others in the Leckie mine some 3 miles farther east shows their distribution to be more than local.

In each case the coal containing the boulders was found to be the Sewell seam (Sharon of Pennsylvania and Ohio) coming in the lower half of the New River group of Pottsville age.

ERRATICS PREVIOUSLY REPORTED FROM COALS

In the United States the presence of boulders in coal has been known for several years. The first known discovery was that by E. B. Andrews[1] of a quartzite boulder, measuring 12×17 inches, imbedded partly in the coal and partly in the shale overlying the

[1] "Report of Work in the Second Geological District during 1870," *Geol. Surv. of Ohio Report of Progress 1870*, p. 78.

Nelsonville coal bed at Zaleski, Ohio. Andrews suggested that the boulder had been transported by river or shore ice. In 1892 Orton[1] reported the finding of an angular vein-quartz boulder from the Sharon coal of Ohio. Prior to this date the boulders had come from the Middle Kittanning bed at Zaleski. Dana[2] reported that F. H. Bradley found a quartzite boulder measuring 4×6 inches in the middle of a coal bed mined at Clear Creek in eastern Tennessee. Dana concluded that this boulder and the one reported by Andrews may have been rafted down by floating trees. McCallie,[3] in 1903, reported a boulder from the coal of eastern Tennessee. Professor A. C. Gill, who has found similar erratics in the coals of eastern Tennessee, writes me as follows:

> . . . . there were three or more well-rounded pebbles, the largest of which was 3 or more inches in length, occurring in a fire clay above one of the thinner coal beds in the Pennsylvanian of Cumberland County, Tennessee. I had a section cut from the largest, and it proved to be a very compact quartzite of about 1 mm. grain size. . . . .

David White[4] reported the discovery of a quartzite boulder in the New River coal field of West Virginia. Dr. White suggested that the character of the rounding seemed to indicate fluviatile action, and suggested that a more or less open lane through the coal swamp had existed, permitting the transportation of boulders by floating drift.

Erratics in coal were known in Europe before their discovery in America, and have been reported from the coals of England, Germany, Austria, France, and Belgium. In 1864 Roemer[5] described three small fragments from a coal bed in Upper Silesia. These were of crystalline rock unlike anything known in Silesia. In 1885,

[1] Edward Orton, "On the Occurrence of a Quartz Boulder in the Sharon Coal of Northeastern Ohio," *Amer. Jour. Sci.*, Vol. XLIV (1892), pp. 62–63.

[2] J. D. Dana, *Manual of Geology* (4th ed., 1895), p. 664.

[3] S. W. McCallie, "An Erratic Boulder from the Coal Measures of Tennessee," *Amer. Geol.*, Vol. XXXI (1903), pp. 46–47.

[4] David White, "Occurrence of Transported Boulders in Coal Beds," *Wash. Acad. Sci.* (1915).

[5] F. Roemer, "Über das Vorkommen von Gneiss-und-Granulit-Geschieben in einem Steinkohlenflotze oberschlesiens," *Zeitsch. Deutsch. Geol. Gesell.*, Vol. XVI (1864), pp. 615–17.

D. Stur[1] gave a summary of knowledge of such occurrences up to that time.

Erratics are not limited to coal but have been found in limestone and shale. The well-known erratics in the Caney shale of Oklahoma are now believed to have been transported by floating ice. Twenhofel[2] has reported granite boulders in Pennsylvanian shale in Kansas. Some uncertainty is held regarding their age, but Twenhofel believes them to be contemporaneous with the shale and to have been transported either by glaciers or floating ice in Pennsylvanian time and deposited in mud laid down in quiet water.

Savage and Griffin[3] have recorded the occurrence of crystalline boulders in Pennsylvanian limestone in Illinois and have concluded that they were derived from rocks in northern Wisconsin or farther northeast and were brought down a southward-flowing river in masses of floating ice and carried out into the Pennsylvanian basin. These authors have concluded that "if this interpretation is correct, it adds another link to the chain of evidence showing that during a part of the late Pennsylvanian time there was a cool temperate climate with cold winters in central North America."

NUMBER, SIZE, AND SHAPE OF BOULDERS, AND THEIR POSITION IN THE COAL SEAM

Table I shows the number of boulders, their weight, greatest dimensions, kind of rock, remarks, and slide number. A glance at this table shows that the greater number have been taken from the New River and Pocahontas Consolidated mine at Leslie, and the adjoining Margarette mine of the Margarette Coal Company at Marfrance. The presence of boulders in these mines has been known for several years, but it was only during 1929 and 1930, and at the writer's request, that they were saved. During this time forty boulders were collected, which probably represent only a fraction of the total number that must be buried beneath the dump. It can be seen

[1] D. Stur, *Über die Flötzen reiner Steinkohle enthaltenen Stein-Rundmassen, etc.*, pp. 613–47.

[2] W. H. Twenhofel, "Granite Boulders in Pennsylvanian Strata of Kansas," *Amer. Jour. Sci.*, Vol. XLIII, pp. 363–80.

[3] T. E. Savage and Judson R. Griffin, "Significance of Crystalline Boulders in Pennsylvanian Limestone in Illinois," *Bull. G.S.A.*, Vol. XXXIX (1928), pp. 421–28.

TABLE I

BOULDERS FROM SEWELL COAL IN GREENBRIER COUNTY, WEST VIRGINIA

No.	Mine	Weight Pounds	Dimensions (Inches)			Kind of Rock	Remarks	Slide No.
			Greatest Length	Width	Height			
1	Margarette	161½	19	15	14	Quartzite, gray	From lower half of coal	1
2	Margarette	58	14	12	8	Sandstone, gray, medium-grained, quartzitic	From lower half of coal	2
3	Margarette	25	11	8	6	Quartzite, gray	Kidney-shaped	3
4	Leslie	22	10½	7½	5½	Quartzite, gray	From roof shales	.....
5	Margarette	10½	9½	4	5	Sandstone, dark, carbonaceous	Rectangular with rounded edges	4
6	Margarette	7½	5½	4	4	Quartzite, dark to white	Vein-quartz? very compact	.....
7	Margarette	3¼	5	4¾	3	Sandstone, grayish-white	Medium grain size	5
8	Leslie	17¼	7½	6	5½	Quartzite, dark-gray	Rectangular block with rounded edges	.....
9	Margarette	17½	11	7	6	Sandstone, gray, fine-grained	Estimated original weight, 21 pounds	6
10	Leslie	12¼	7	7	5½	Quartzite, gray	Polished	.....
11	Leslie	10½	10½	3¾	4¾	Quartzite, gray	Broken in transportation	.....
12	Margarette	10¾	10½	7	4	Sandstone conglomerate, gray	Cut in quartz vein	7
13	Leslie	10¼	9	4½	4	Quartzite, grayish-white	Estimated original weight, 12 pounds	.....
14	Leckie	12	8½	4	3¾	Quartzite, gray	Well polished	.....
15	Margarette	8½	6½	5	4½	Quartzite, gray	Subangular	.....
16	Leslie	7¾	6½	6	4	Quartzite, gray	Elliptical, well polished	.....
17	Leslie	5	5	4	4	Quartzite, gray to maroon	Subangular, three flat faces	8
18	Leslie	4½	7½	4½	3	Quartzite, gray	Bottom side flat	.....
19	Margarette	4½	5	4	4	Quartzite, gray	Subangular (see 15, 17), striations	.....
20	Margarette	4	.....	.....	0	Quartzite, altered	Spherical, cut by quartz vein, sericite, quartz, and chlorite	9
21	Leslie	3½	5½	4½	2½	Conglomerate, metamorphosed	Quartz grains 5 mm. to very fine. Chlorite, sericite, and secondary quartz, pyrite	10
22	Leslie	3	.....	.....	.....	Vein-quartz	Well rounded	.....
23	Leslie	3⅛	5	4¼	3	Quartzite, gray	Well rounded	.....

TABLE I—*Continued*

No.	Mine	Weight Pounds	Dimensions (Inches)			Kind of Rock	Remarks	Slide No.
			Greatest Length	Width	Height			
24	Margarette	$2\frac{5}{8}$	5	$3\frac{1}{2}$	$2\frac{1}{2}$	Quartzite, cut by quartz vein	Angular	11
25	Margarette	$2\frac{3}{8}$	$4\frac{3}{4}$	$4\frac{1}{2}$	2	Conglomerate, metamorphosed	Cavities. Blue and clear quartz, pyrite, some feldspar, altered, dark inclusions	12
26	Leslie	6				Vein-quartz	Broken, originally well rounded	
27	Leslie	$2\frac{3}{16}$	$5\frac{1}{2}$	3	$2\frac{1}{2}$	Quartzite, gray	Kidney-shaped, parallel pyrite veins	
28	Leslie	25				Granite, altered	Broken, weight estimated	13
29	Margarette	2				Conglomerate, metamorphosed	Subangular, much pyrite	14
30	Leslie	1	$4\frac{1}{4}$	$2\frac{1}{2}$	$1\frac{3}{4}$	Vein-quartz	Elongate, rounded pitted surfaces	
31	Margarette	1	$3\frac{1}{2}$	$2\frac{1}{2}$	2	Quartzite	Faceted faces	
32	Leslie	$\frac{5}{8}$	$3\frac{1}{4}$	2	$1\frac{1}{2}$	Quartzite	Smooth, kidney-shaped	
33	Margarette	$\frac{3}{8}$	3	$2\frac{2}{3}$	$2\frac{1}{2}$	Quartzite		
34	Leslie	2				Quartzite, bluish-gray	Broken, rectangular cross-sections	
35	Leslie	5				Quartzite, gray to maroon	Compare with No. 17	
36	Margarette	$1\frac{5}{8}$	$3\frac{1}{2}$	2	2	Sandstone, grayish-white, quartzitic	Pyrite scattered through	15
37	Leslie					Quartzite, impure, conglomeratic	In coal specimens. See Figure 2	16
38	Leslie					Sandstone, gray, fine-grained	Clayey cementing material, now mostly sericite	17
39	Leslie					Quartz porphyry (?) highly altered	Fine-grained quartz; kaolinite (?) sericite, chlorite, pyrite	18
40	Leslie	$\frac{1}{2}$ oz.				Vein-quartz	Small walnut	

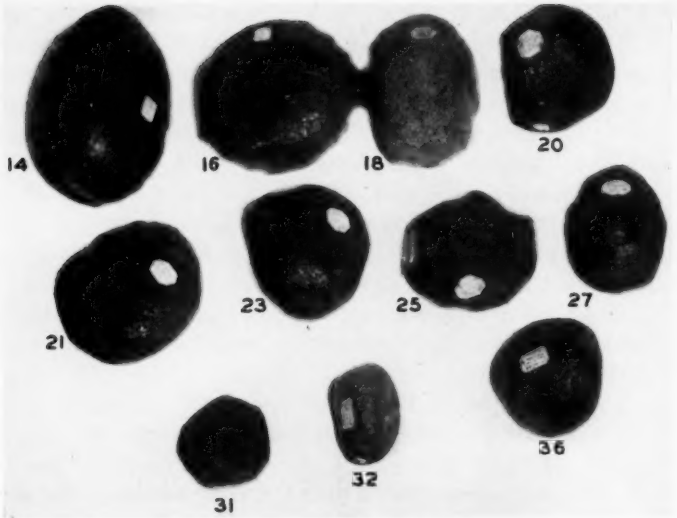
from the table that they vary in weight from 161½ pounds to ½ ounce, the average being approximately 12 pounds. Even though all are partially or totally rounded, their greatest dimensions are given for the purpose of comparison. The boulders all show characteristic rounding by fluviatile action, some being beautifully polished, although the degree of roundness varies. Boulder Nos. 6, 8, 12, 15, 19, and 24 (Fig. 1, *A* and *B*) might better be described as subangular, the angularity probably being due to fracturing along planes of weakness, in transit, with subsequent abrasion sufficient only to round these edges. A few of the boulders show etching or grooves on the flattened faces, although the faces are not sufficiently flat, nor the grooves sufficiently straight, to indicate with certainty ice abrasion.

As would be expected, the greater number of boulders were removed in mining, and consequently were not seen in place by the writer. Figure 2, *A*, Nos. 37, 38, 39, shows three of the smaller boulders in place, these coming from the lower portion of the coal which is in part bony and has a few small fragments of shale scattered through the coal. On the upper surface of both blocks, and particularly embedded in a large calamite, are numerous crystals of secondary gypsum. The largest boulder, Figure 3, No. 1, rested upon the floor of the mine and extended its height of 14 inches up in the coal. It was struck by the cutting machine in such a way as to place its position definitely. A great number of the boulders were found in the clean coal, with no other foreign material present. Others were found in the roof and extended down into the coal. Most, if not all, were coated with coal, which in most cases shows slickensided surfaces, evidencing differential compaction around the erratic. The presence of the boulders scattered through the coal at different horizons was established beyond doubt.

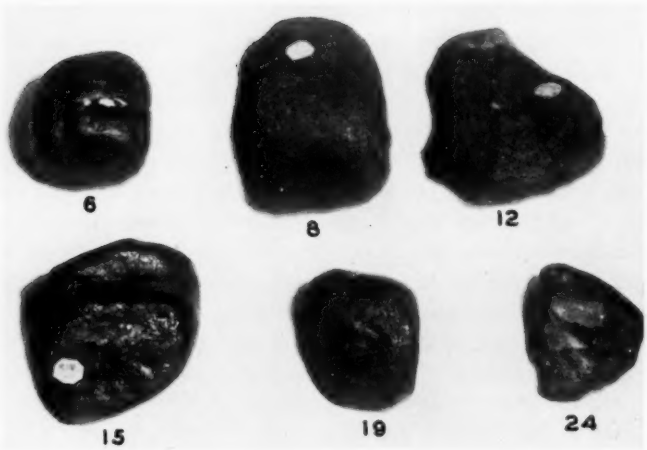
Figure 2, *A*, Nos. 37 and 39, shows clearly continuous laminations bending around the boulder in such a way as to place the erratic as previous to, or contemporaneous with, the horizon it now occupies rather than having sunk into an unconsolidated peat bog.

CHARACTER OF BOULDERS

There are 40 specimens in the collection, of which 24 are quartzites, 7 are sandstones, 4 are vein-quartz, 3 are conglomerates, 1



A



B

FIG. 1.—*A*, upper view, shows rounded and well-polished boulders. *B*, lower view, shows subangular boulders.

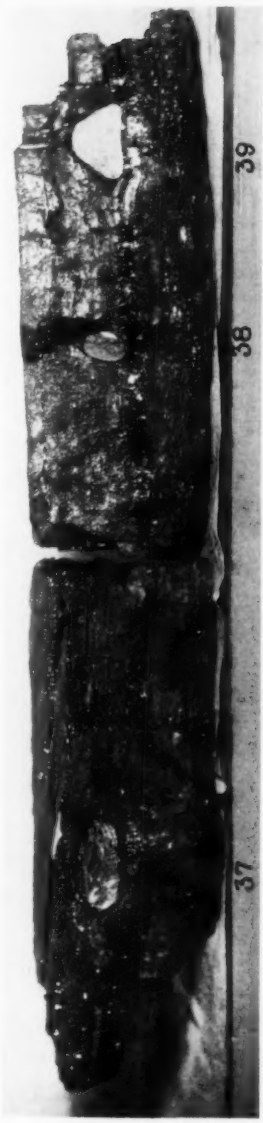


FIG. 24.—Showing boulders in place

granite, and 1 quartz porphyry. The quartzites are predominantly gray, but varying from grayish white to a reddish or maroon hue. The texture is mostly quite compact and averages approximately 1 mm. grain size. They vary in size from the largest weighing 161½ pounds to the smallest weighing less than one pound.

The seven sandstone boulders vary from grayish white to dark in color, and from fine-grained to conglomeratic in texture. The cementing material is chlorite, sericite, and secondary pyrite. These boulders range in weight from 58 pounds to 1⅝ pounds. There are four specimens of milk-white vein-quartz and three conglomerates. The conglomerates have all been somewhat metamorphosed; and sericite, chlorite, and secondary quartz have been developed. These all contain considerable pyrite.

The two specimens that are probably of most interest are in Figure 3 —Nos. 28 and 39. The former is identified as an altered granite. The quartz and muscovite mica are well preserved, while the white soft clayey material is taken to be altered feldspar. The latter specimen, which was examined by Dr. J. H. C. Martens (also Fig. 3, Nos. 20, 21, 37, 38), is questionably a very much altered quartz porphyry. The specimen contains large grains of quartz surrounded by a fine-grained mixture of

quartz, kaolinite(?), sericite, and chlorite, with a great deal of pyrite, both as small disseminated crystals and as continuous masses enveloping many small quartz grains. Dr. Martens states that the

FIG. 2*B*.—Showing the largest and smallest specimens

association suggests a quartz porphyry but that it may possibly be an altered sandstone.

PROBABLE SOURCE OF BOULDERS

The character of the boulders, as shown by the preceding descriptions, marks them, with one or two exceptions, as being unlike rocks known to occur in West Virginia. The nearest source of similar

rocks is the crystalline area of the Blue Ridge, Virginia, a distance of some 60 miles to the east.

FIG. 3.—Erratics from Sewell coal, Greenbrier County, West Virginia. Number 28 is a granite that was broken by the miners. (See Table I.)

It is therefore assumed that a river in Pennsylvanian time, with its source in the crystallines of what is now the Blue Ridge, flowing in a westerly direction, carried the boulders into the Pennsylvanian basin.

POSSIBLE AGENTS OF TRANSPORTATION

In discussing the possible agents of transportation, both water and ice will be considered. Under the former it is further necessary to consider some rafting agent, as it is unlikely that a stream would transport boulders of this size so far from their original source without some such auxiliary agent.

To account for the presence of boulders in coal, the view previously expressed by most geologists is that they were held in the roots of trees and rafted to their present position. To assume that all of these boulders, especially the larger ones (see Fig. 3, Nos. 1, 2, 3), could have been carried to their present location without considerable quantities of other foreign material, calls for a stretch of the imagination. That some may have been so transported is not doubted. It does not seem logical, however, that a stream sufficiently large to raft trees that could carry some of the boulders here noted would be found in a coal-forming environment. A stream of such size would certainly "wash out" the peat bog itself. Furthermore, the presence of boulders at various horizons in the coal would necessitate the presence of the stream throughout the entire time of the accumulation of the coal-making material.

The second method of transportation, which is looked upon with favor by some but strenuously objected to by others, is ice. The prevailing opinion seems to be that Pennsylvanian temperatures were not sufficiently low for the formation of ice. Considerable evidence, however, has been advanced to show that during a part of the Pennsylvanian, and especially in the higher altitudes, ice was present for a portion of the year, a view in which the writer concurs. The present boulders, however, do not show the characteristics common to those transported by ice, such as faceted faces or striations. It does not follow, however, that river or shore ice may not have carried these boulders from beaches or along the banks of streams into the Pottsville basin. This, however, would be expected prior to or following the coal accumulation, and could account for the boulders only in the underclay or the overlying sediments. It has already been pointed out that the boulders do not occur at any one particular horizon in the seam, but may be found at any level from the under-

clay to the roof shales. It should be stated, however, that the majority are found in the lower part of the seam.

If we may assume immediately preceding the coal accumulation a stream with a very low gradient, along which boulders had been deposited by transporting agents, gradually being encroached upon by coal vegetation, it would be possible for trees by overturning to draw the erratics up into the peat bog . It is known that succeeding vegetation continued to extend its roots into the peat bog. This condition could and would be repeated at succeeding intervals so as to lift the boulders to any level in the accumulating material. Such an environment could be explained by a slight uplift near the mouth of a river that formerly had a rather steep gradient.

CONCLUSIONS

The purpose of this paper is to call attention to the facts regarding the present discovery rather than to offer a definite explanation to account for the presence of erratics in coal.

Three possible explanations have been offered: (1) ice; (2) rafting in the roots of trees; (3) and the elevation of boulders into the bog by the overturning of trees rooted in an old river channel underlying the bog. This same process could be repeated during the coal-forming period and could account for the boulders at different levels in the seam.

AVAILABLE RELIEF AS A FACTOR OF CONTROL IN THE PROFILE OF A LAND FORM[1]

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ABSTRACT

Available relief is defined as the vertical distance from an original, fairly flat upland down to the initial grade of the streams. If available relief is less than about 200–300 feet, valley flats are formed before the upland is destroyed, but if it exceeds 200–300 feet the upland disappears before valley flats appear. Commonly, then, 200–300 feet constitutes a critical relief at which valley flats begin to form just as the upland disappears. Certain inferences arising from the observations are discussed.

INTRODUCTION

The observations forming the basis of the ideas here presented were made a number of years ago in the basin of Olentangy River, especially among the tributaries immediately north of Columbus, Ohio. They drain an area which possesses three prominent topographic elements: valley flats, steep valley walls, and broad flat uplands. Detailed study discredited the initial belief that in most cases change of lithology from drift above to shale below caused the development of the flats along the streams. The conditions permitting the existence of the two flats—the upland and the lowland—will be the chief interest of the present paper.

Subsequent observations have been made on parts of the drift region of the Central Lowland, the lake plains adjacent to Lakes Erie and Ontario, the northern Appalachian region, and parts of the Atlantic Coastal Plain. Within the last two years observations have been extended and verified by the use of topographic maps and an attempt has been made to systematize the facts obtained both from the field and from the maps. Since it is impracticable to reproduce a large number of topographic maps, a list sufficiently adequate will be cited in order that anyone, if he so desires, may place them in sequence as given and pass judgment for himself on the ideas here presented.

[1] Presented in abstract form before the Geological Society of America, Toronto, Canada, December 31, 1930.

Assumptions and definitions.—Necessary assumptions include a humid climate like that of the Eastern United States; normal stream erosion; a more or less smooth initial surface; a certain stability of the level of baselevel; and, apparently, though perhaps not necessarily, rather uniform lithology and simple structure. Some of these assumptions may be found to be wholly superfluous and others not included may be vitally important.

Drainage relief refers to the vertical distance through which rain water moves over the ground from the time the water first strikes the surface until it joins a definite stream. Available relief refers to the vertical distance from the original upland down to the level at which a valley flat begins to develop. The critical relief is that amount of available relief which exists when the final disappearance of the upland flat coincides with the initial appearance of the valley flat. After observation had established with some assurance the fact that certain amounts of drainage relief permit the simultaneous existence of upland and lowland flats, further work sought to determine the size of the factor called critical relief.

Acknowledgments.—The writer wishes to express his gratitude to the Research Committee of the Graduate School of Ohio State University for funds to obtain a research assistant whose help made possible the completion of the office work and the preparation of the profiles.

LOW AVAILABLE RELIEF

The designations, low, medium, and high, applied to relief, are used in a descriptive fashion for convenience only. Low available relief arbitrarily includes any amount up to 150 feet.

A lower flat develops to a considerable extent long before the upper disappears, if available relief is low. As the relief increases, the two flats in existence at the same time constitute proportionately less and less of the total area. More of the surface has become slope. Figure 1 shows a profile smoothed and generalized from some twenty or more profiles which were selected as typical of as many maps. Figure 2 shows a generalized profile taken from maps with available relief from about 80 to 150 feet.

A fairly representative list of maps has been selected and is appended in sequence, the lowest available relief first. If the maps are

inspected in order, the effect of increasing relief on the amount of upper flat remaining and the amount of lower developed will be easily seen. A vast difference, for instance, exists between the Winton, North Carolina, map with a drainage relief of 10–40 feet

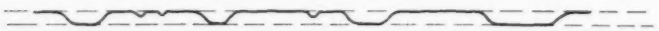

FIG. 1.—A composite profile characteristic of regions with low available relief, i.e., up to 60 feet. Available relief in all the figures is represented by the vertical distance between the upper and lower dashed lines.

FIG. 2.—A composite profile characteristic of regions with available relief from 80 to 150 feet.

FIG. 3.—A composite profile characteristic of regions with available relief approximating the critical value.

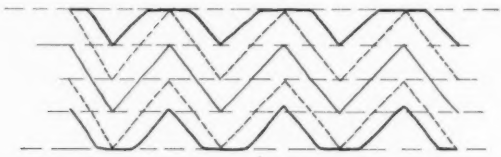

FIG. 4.—A diagram constructed to show the evolution of a land profile in regions of high available relief. The relations of the original upland to the succeeding lowland and the series of events separating the two are evident. In terms of the geographic cycle a region represented by the profiles would be in the stage of maturity during a long interval of time.

and the Pella, Iowa, Melcher, Iowa, or Carrollton, Ohio, maps with drainage reliefs of 100–200 feet.

Suffolk, Va.–N.C.	Gillespie, Ill.
Winton, N.C.	Colchester, Ill.
Falkland, N.C.	Coharie, N.C.
Williamston, N.C.	Girard, Pa.
Oberlin, Ohio	Dublin, Ohio
Waukee, Iowa	Springfield, Ill.

Mercersburg, Pa.
Macomb, Ill.
King William, Va.
Mt. Carmel, Ill.–Ind.
Brighton, Ill.
Milo, Iowa
Griggsville, Ill.
Albia, Iowa
Havana, Ill.
Vermont, Ill.
Pella, Iowa
Melcher, Iowa

MEDIUM AVAILABLE RELIEF AND THE CRITICAL

Medium relief, which is taken from 150 to about 300 feet, permits little upper flat (something like 15 per cent and less) to remain at the time when the lower flat begins to form. As the available relief increases less upland remains until, at the critical value, the disappearance of the upland coincides with approximately the appearance of the lowland. Figure 3 shows a generalized profile which suggests a so-called mature topography dominated by slopes.

A further increase in available relief prohibits the existence of upland and lowland at the same time: the relief has exceeded the critical. Very commonly the figure for critical relief lies between 200 and 300 feet. If it is less, both flats may exist simultaneously; if it is greater, the upper is gone before the lower is started. Critical relief rarely attains 400 feet and only under exceptional circumstances does it appear to exceed 400 feet.

The maps listed below illustrate the conditions described in this section. A careful study and comparison not only of entire maps but more especially of separate localities on a single map will reveal the important part played by the factor called critical relief.

Carrollton, Ohio
Oelwein, Iowa
Zelienople, Pa.
Barnesboro, Pa.
Foxburg, Pa.
Fairmont, W.Va.
Elders Ridge, Pa.
Beaver, Pa.
Pittsburgh, Pa.

HIGH AVAILABLE RELIEF

High available relief for present purposes is any figure distinctly above the critical. Uplands and lowlands do not exist at the same time, for the relief is so great that weathering and erosion destroy all traces of the upper flat before the streams have an opportunity to start a lower one.

Any relief, in excess of the critical, causes available relief to exceed the drainage relief at all times. When the last remnant of original upland remains, the available relief exceeds the drainage relief by the number of feet a particular stream, or the average over a particular area, must cut downward to grade. A continuance of denudation lowers the crests of the ridges, which last held parts of the original upland. When the streams begin to form the lowland, the available relief exceeds the drainage relief by the number of feet the secondary upland level (general level of the ridges) lies below the original upland. This somewhat tedious explanation is not only a necessary description of the topic in hand but also a necessary introduction to portions of the discussion. Figure 4 is a composite profile illustrating diagrammatically the changes occurring in a region of high available relief.

The maps listed below possess a drainage relief from 300 to 700 feet, or more. What was the available relief in the region shown on the Bucu sheet? How high was the original upland above the general level of the present-day ridges? These questions instantly bring to mind certain ideas concerned with the preservation of ancient land forms.

Mannington, W.Va.–Pa.	Bucu, Va.
Burnsville, W.Va.	Bellefonte, Pa.

SUMMARY

Available relief seems to be an important factor of control in the development of surface profile. A relief below 200–300 feet permits the simultaneous existence of two flats, an upper representing the original upland and a lower representing the new valley flats. At 200–300 feet the relief attains the critical for most cases and the upper flat goes out of existence as the lower comes in. Beyond the critical relief, the upper flat is gone before the lower appears, and, when the lower appears, the general upland level has been lowered the amount by which the available exceeds the critical relief.

The change in surface profile incident to increased available relief may be described in a slightly different manner. Low relief permits the existence of two flats far into tributary areas. As the relief increases, fewer tributary valleys develop flats and fewer secondary

divides retain them. At last, when the critical relief is approached, only the main divide and the main stream possess flat areas simultaneously. These statements are generalized and averaged; they probably do not apply universally to all specific areas.

DISCUSSION

Certain inferences and deductions arising from the foregoing considerations may be treated, in more proper fashion, separately from the observational portion of the study. The present work, it is thought, actually lies in the borderland connecting the dynamic cycle[1] of stream systems with the geographic cycle of land forms.

When the development of valleys is studied with the two-flat idea in mind, it is immediately apparent that the valleys pass through two distinct and prominent stages only: first, a stage preceding the existence of a valley flat; and second, a stage succeeding the initiation of a flat. The inititaion of the valley flat, in other words, sharply divides the history of a valley into two easily recognized stages which are closely related not only to stream activity but also to the evolution of topography. Vertical corrasion, in sum total effect, dominates prior to the existence of the valley flat and lateral corrasion after the flat is begun. The first stage corresponds to youth in the geographic cycle and the second both to maturity and old age.

Aside from the initiation of a lower flat as a division point, the development of a valley is extremely gradual and uniform—so gradual, in fact, that two phases in development must be separated by a distinct time interval to permit the eye to note perceptible changes. Maturity can be differentiated rather easily from old age in a large way, but, in detail, the two can be differentiated only with great difficulty if at all. Therefore, the natural twofold division of valley history into pre-valley flat and post-valley flat, or pre-grade and post-grade attainment, has a very real existence from the dynamic as well as from the geomorphologic standpoint.

Physiography has given an undue amount of attention to valleys in comparison with that given divides. A study of the origin, development, and patterns of divides, for instance, might give results

[1] For the dynamic cycle see: "The Development of Drainage Systems—a Synoptic View," *Geog. Rev.* (July, 1931), p. 475.

just as interesting as valleys have given. The present work touches the divides in one matter. Their history may be studied, first, during the existence of the upland flat when its area constantly decreases, when its pattern varies, and when its relations to available relief modify the surface profile; and second, after the disappearance of the upland flat when the ridge crests, which at first coincide with the level of the former upland, are gradually reduced in altitude and when the pattern undergoes a series of alterations in striking contrast to that of the original upland. At once the queries arise, "Will not these ridge crests be lowered about at the same rate provided they, or a certain group of them, offer approximately equal resistance to destructive processes?" and, "What will be the effect of such uniform lowering on interpretations of the elevation and condition of the original upland however it came into existence at the beginning?"

The foregoing discussion immediately suggests that available relief must be an influential factor in the preservation of uplifted peneplains. In view of the control exerted by available relief on the simultaneous existence of two flats, the preservation of a peneplain situated beyond the ordinary critical relief requires the presence of special conditions. The possible uniform lowering of ridge crests and the factor of critical relief must be taken into account, it seems, in the geomorphologic history of a region. Will the conditions in any given area permit the preservation of peneplain remnants, or, if the ordinary critical relief is exceeded, what are the special conditions permitting preservation? For how long a time will a divide, after having been reduced practically to a line, maintain even approximately the same elevation as the supposed original upland of which it formed a part? These questions require answers in many physiographic studies, and the less the evidence from which history is inferred the more urgent the requirement.

A knowledge of the exact influence of climate on land forms would be of great interest. In fact, no rashness is intended by the statement that climate might well be the predominant factor influencing the nature of physiographic development. Two points merit attention at present. An arid climate apparently increases the amount of relief which is critical for the simultaneous existence of two flats.

Further, many valleys seem to be widened by the lateral recession of their walls. The influence of these two factors prolongs the existence of the upper flat approximately in its original condition over long intervals of time except for the effects of wind and rain-wash.

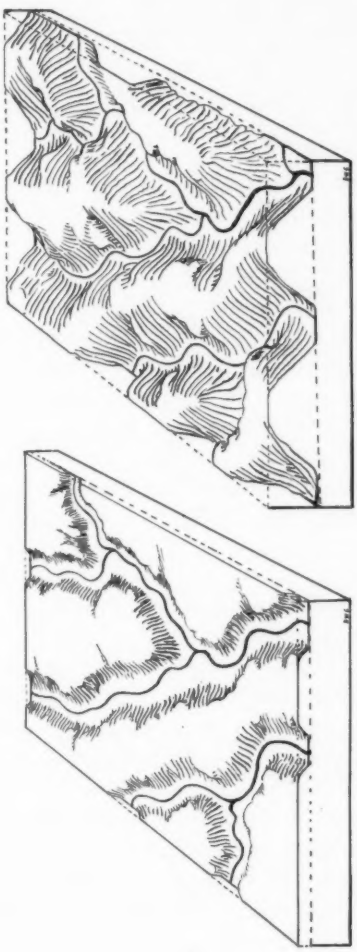

FIG. 6

FIG. 5

FIG. 5.—A block diagram to illustrate the nature of the topography in regions of low available relief. The vertical distance between the dashed lines represents available relief in this and the following diagrams.

FIG. 6.—The nature of the topography in a region with available relief of about 150 feet or slightly more.

RELATIONSHIPS

The simultaneous existence of two flats is chiefly a function of climate, available relief, rock and structure, and the distribution of streams. Under a humid climate, such as that assumed for the present study, available relief becomes a mathematical relationship expressed by the width, density of distribution, and depth of valleys.

Differential rock resistance and deformed structures undoubtedly modify the effective value of critical relief. An intervalley area of tilted resistant rock between valleys on nonresistant rock stands

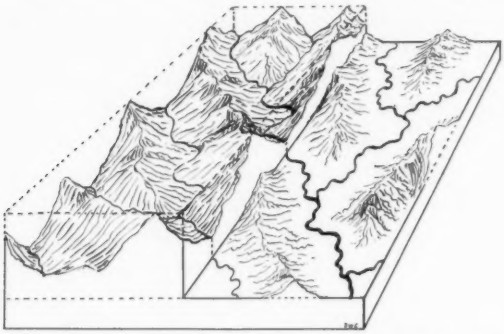

FIG. 7.—The evolution of topography in a region whose available relief exceeds the critical value. The left-hand portion of the block represents a stage just after the disappearance of the upland and the right-hand portion represents a much later stage when the intervalley areas have been lowered and when the lowland has appeared.

much closer to the original upland than it would if the rocks were uniformly resistant under valley and ridge alike.

The rate of land elevation, it would seem, modifies surface profile to a considerable extent. Rapid uplift increases the numerical value of critical relief; hence two flats may exist at the same time with an available relief higher than the ordinary critical value. Slow uplift decreases the value of critical relief; hence two flats may exist at the same time only with an available relief lower than the ordinary critical amount. If uplift is sufficiently slow and prolonged, the divides may be rounded off and two flats may never be present at the same time. Uplift is used in the sense that it effects rejuvenation.

A study of available relief permits a word to be said about the relations of the dynamic to the geographic cycle. Maximum extension apparently precedes maturity if available relief is low, as for instance on the Barclay, Maryland–Delaware, sheet. In fact, the surface profile of a region with low available relief ill becomes the common conception of the geographic cycle (Fig. 1). Maximum extension apparently coincides with maturity if available relief equals or exceeds critical relief.

In the dynamic cycle maximum extension endures for an interval of time dependent upon the amount of available relief. If the amount is small (Milo, Iowa, sheet) the trunk portions of a drainage system show the activities of integration long before the outlying portions have finished extension. Extension then reaches a maximum at a point nearly, if not quite, impossible to determine. If the amount equals or exceeds critical relief, maximum extension and, hence, maturity endure for a length of time roughly proportional to the amount by which available exceeds critical relief, that is, for the length of time from the disappearance of the upper flat until after the appearance of the lower.

Surface profile and surface form depend to a great extent upon the factor of available relief under the assumed conditions of climate and geology. The stages of the geographic cycle considered at their mid-points seem to fit best of all in regions of high relief under a moist climate.

REVIEWS

"Geologic History of the Yosemite Valley (California)." By FRANÇOIS E. MATTHES. *U.S. Geol. Surv. Professional Paper 160.* 1930. Pp. vi+137. figs. 38; pls. 52 (incl. 3 maps in pocket, 1 folding diagram, and 2 folding geol. maps).

Occasionally in the history of science there appears a work so excellent, so comprehensive, that it becomes immediately a classic. Such a newborn classic is the long-awaited "professional paper" by Matthes on the Yosemite Valley. Much investigation of each minor detail of this unusually beautiful canyon is justified by a profound and widespread popular interest. It is fitting also that this information should be set forth in as simple and straightforward a style as possible. Matthes has demonstrated that clear and cogent reasoning can be expressed with a minimum of that scientific jargon used so unhappily by less careful writers. Large issues of importance to every geomorphologist are discussed with great breadth of insight and a wealth of detail, largely of a quantitative nature. These issues are: (1) the geologic history of the Sierra Nevada, one of the great mountain ranges of the world; (2) the alternating stages of rapid uplift and intervening quiescence; (3) the threefold glaciation of the region; (4) the amount of glacial excavation; (5) the influence of jointing on erosion and the relative durability of unjointed monoliths.

The classic paper of Lindgren ("Gold-Bearing Gravels of the Sierra Nevada," *U.S. Geol. Surv., Professional Paper 73* [1911]) records the physiographic history of the mountains and the geologic dates of the plant remains in the gravels have been recently confirmed by Chaney (Abstract, *Preliminary List Meeting Cordilleran Section Geol. Soc. Amer.*, p. 8, 1931). In the area of Merced River the sequence of these early events is not so clear, and the evidence on which descriptions of these earlier cycles might be based is omitted by Matthes. The unevennesses of the Cretaceous peneplain, together with the valleys of Eocene and Miocene time, are considered by Matthes to form the "Broad Valley" stage with which his history of the Yosemite Canyon begins. A similar valley is characteristic of the Stanislaus River, but it was invaded by lava and beneath this cover (on the well-known Table Mountain) plant and animal remains of Miocene age are found. Thus Miocene is considered the date of the "Broad Valley"

stage. At this time the streams tributary to the Merced were adjusted to the structure and had northwest-southeast courses in the belts of weaker rocks. Uplift then occurred and an inner valley was formed, the "Mountain Valley" stage, during which Merced River reached a mature grade. Many of its tributaries, however, were unable to keep pace with the main stream and were left in hanging valleys from which their waters plunged in steep rapids into the main canyon. The great uplift of Pleistocene time induced the carving of the deep canyon of the Merced, the primitive Yosemite Valley, which was subsequently enlarged and carved by glacial action to its present spectacular beauty.

The alternate stages of uplift and quiescence, described above, rest on the tangible evidence of the three sets of hanging valleys. The Merced is approximately at right angles to the axis of uplift of the Sierra Nevada, and it quickly readjusts its gradient after uplift. The tributary valleys lie parallel to the axis of uplift; and, by reason of their relatively small volume and lack of increase in gradient, except at their junction with the Merced, they fail to keep pace in down-cutting with the master stream. Those whose courses lie over unjointed, highly resistant granite have been unable to deepen their channels appreciably since the major uplift began at the close of Miocene time. They form the upper set of hanging valleys and preserve the "Broad Valley" topography. Projection of their longitudinal profiles forward to the axis of the canyon of the Merced (making due allowance for glacial erosion and other factors) gives a series of accordant elevations which correspond to points on the profile of a mature river, and hence indicate an old pre-uplift, and Miocene profile of the Merced with respect to which the tributaries were graded. The projection of the gradients of the next lower set of hanging valleys that are eroded in moderately jointed granite of intermediate resistance produces on the axis of the Merced a second profile several hundred feet lower. This profile is characteristic of a river in the submature stage of development, and indicates that the strong post-Miocene uplift was followed by a sufficiently lengthy period of relative quiescence to allow the development of the submature "Mountain Valley" stage. The lowest set of hanging valleys, developed in closely fractured rock of low durability, can in the same way be projected to indicate a third profile of the Merced more than a thousand feet below the second. This is the "Canyon" stage of pre-glacial time.

The use of this method of determining the amount of uplift and the characteristic gradients of the valley of Merced River at each stage requires first-grade maps and an intimate knowledge of each tributary

valley. The gradients must be projected as concave curves, and the choice of the curve depends on refined judgment. For this work Matthes is eminently equipped both by long experience and by his skill in mapping. He has also applied the method in the Kings River Canyon (*Sierra Club Bull.*, Vol. XII [1926], pp. 224–36), and an extension of the method would give an intimate knowledge of the uplift of the Sierra Nevada as yet unattained in other mountainous regions.

In the study of the glacial history of the Yosemite Valley, Matthes uses the same care that characterizes his analysis of the physiographic history. The main lines of evidence used in discriminating the glacial succession are: frontal and lateral moraines, glacial striae and polish, and differential weathering of the glacial surfaces. Glaciation of the valley is threefold. The oldest ice invasion, tentatively correlated with the Kansan or Nebraskan, is known only from the presence of greatly weathered boulders of quartzite and siliceous granite that rest on a gently sloping shoulder of Glacier Point from 200 to 400 feet above the highest moraine of the next oldest stage. The second stage, tentatively correlated with the Kansan or Illinoisan, covered a larger area and had thicker ice masses than the last or Wisconsin stage.

Comparison of the pre-glacial profile of Merced River, obtained as heretofore explained, with the existing and post-glacial profiles, leaves little doubt as to the power of valley glaciers to erode. At the lower end of the valley the depth of scour measures 500 feet (150 meters), while up the valley it gradually increases to 1500 feet (450 meters). The widening of the valley by ice is revealed by a similar comparison of the cross-profiles of the pre-glacial and post-glacial canyons. The widening measured at right angles to the sides of the valley amounts to fully 1,800 feet (550 meters) in the widest part of Yosemite Valley. Abrupt changes in the amount of widening are coincident with variations in the distribution and arrangement of the joints in the rock. The main Yosemite "chamber" owes its existence to the presence of well-jointed gabbro and diorite into which the glacier was able to quarry with ease. The square head of the valley is explained by the controlling influence exerted by local fracture systems on the glacial quarrying. The great amount of erosion at the head of the valley is due to the fact that the ice was thicker and had more erosive power at this point, and during its maximum stages it plunged into the head of the valley in a mighty cataract with great erosive force.

The steplike longitudinal profile or "glacial stairway" had long been a problem, which is explained by Matthes on the distribution of joints.

In front of each rise of the steps is a body of vertically jointed or sheeted rock that was readily quarried by the glacier. The edge of each step is, however, composed of more massive and obdurate rock that was worn down but slowly, and thus controlled the general level of the step above. Unlike Yosemite Valley and Little Yosemite Valley, the deep and narrow Tenaya Canyon is located on a belt of longitudinal fractures which promoted glacial quarrying in a downward direction with no tendency to the formation of steps or to lateral widening.

The evidence for large-scale glacial excavation rests on the general contrast between the widened Yosemite and the narrow unglaciated canyon of Merced River below El Portal as well as on the detailed comparison of profiles and cross-sections. The arguments of Crosby (*Geol. Soc. Amer. Bull.*, Vol. XXXIX, pp. 1171–81), of Romer (*Mem. Acad. Polonaise Sci. et Lettr.*, Ser. A., Vol. I [1929], pp. 1–253), and others who have minimized glacial erosion are met with a wealth of material fact and a logical analysis.

The deeply cut recesses and gulches that occur throughout the Yosemite region in places where stream or glacial action is at a minimum are explained by Matthes as due to the "destructive action of ground water, frost, torrential rains and snowslides" in zones of minutely fractured rock. Standing in contrast to the recesses, yet in many places carved from the same kind of rock, are the great granite domes such as El Capitan, Half Dome, and others. These smooth-topped masses form the highest elevations and consist of nearly unjointed rock. The rounding at the top is due to concentric, curving cracks from which shells of rock break off. The form is essentially the same whether the dome has been glaciated or not. It appears, therefore, that these great monoliths are destroyed only by reason of their exfoliation and are, and have been, throughout the history of the region, singularly resistant to erosion. The descriptive detail given by Matthes demonstrates clearly the relative effect of both normal and glacial erosion on jointed rocks and on the unjointed monoliths. Full discussion of the origin of exfoliation, especially well shown on the domes, is apparently reserved for later treatment.

In concluding, the reviewer wishes to call attention to the important rôle played in this geomorphological study by the detailed petrographic researches of F. C. Calkins. The conclusions on the effect of jointing in erosion rest not only on detailed observations by Matthes but also on the differentiation of unlike rocks and recognition of like rocks by Calkins.

KIRK BRYAN

Cope: Master Naturalist. By HENRY FAIRFIELD OSBORN, with the co-operation of HELEN ANN WARREN. Princeton University Press, 1931. Pp. xvi+740; figs. 30.

Edward Drinker Cope, although one of the most brilliant of American zoölogists and paleontologists, has remained comparatively unknown to most of his countrymen, even those engaged in scientific work, since his death more than three decades ago. No adequate account of his life has heretofore been published; even such a work as the *Encyclopedia Britannica* does not mention him. It is to be hoped that the volume under review will serve to arouse a wider interest in the career of this brilliant, fiery, but lovable scientist.

The author has used, with striking success, the device of building the story of Cope's life as far as possible around Cope's own narrative of his adventures and experiences as related in letters, first to his father and sister, later to his wife and to his beloved daughter. Even his boyish letters show a keen power of observation and a love of nature which indicate clearly the field of his life-work.

Born of an old Philadelphia Quaker family, Cope was brought up in the idea that he was to lead the life of a gentleman farmer. But, after a comparatively short schooling and some years of practical farm experience, Cope felt himself ill-fitted for this career, and, at the age of twenty, entered the field of natural history.

Here living reptiles and amphibians were at first the center of his interests; he rapidly became a leader in this field and throughout his career continued to make valuable contributions to herpetology. But it was not long before fossil forms attracted his attention and he entered the domain of vertebrate paleontology in which the greater part of his life's work was to be accomplished.

The decade of the seventies was perhaps the happiest and most productive period of Cope's life. Explorations in the western territories were continually opening new and interesting fossil fields, filled with new and strange forms awaiting description. Cope's early financial independence enabled him to devote his entire time to scientific work. The various government surveys of the West afforded opportunities for field explorations, while his modest fortune enabled him to purchase valuable specimens, engage collectors and preparators, and make his own expeditions into the West. His letters from the field in this period give a vivid picture of life in the West in early days and the trials and tribulations of the scientific explorer of that period. Even after a lapse of half a century one can still feel, with Cope, the interest and enthusiasm aroused in the young

scientist by the repeated finding of new fossil localities and horizons. Of special interest was the trip to New Mexico in 1874, where his discovery of the important Eocene deposits of the San Juan basin was made possible only by flagrant disobedience of the orders of his chief, and the trip to the dinosaur beds of Montana, a "raid" conducted by Cope while the hostile Indians of the region were engaged in fighting government troops in another area.

Marsh of New Haven had entered the field of vertebrate paleontology at about the same period, and with these two men, at first friends, both working feverishly for the discovery and description of new forms, it is not astonishing that they soon came into conflict. Primarily clashing on the subject of "priority," it was not long before the conflict became an open one, and from arguments as to possible errors in the dating of publication of scientific papers, it passed to accusations of theft, scientific dishonesty, and deliberate destruction of fossils to prevent their falling into the hands of the other party. No greater contrast can be imagined in personalities than that between the two antagonists, between the brilliant and impulsive Cope, and Marsh, solid, stolid, and steady. Although reaching its climax in a series of bitter articles, inspired by a "yellow journalist," in the *New York Herald* in 1890, the conflict lasted to the end of their lives. It has left, unfortunately, many paleontological snarls to untangle, due to duplication of scientific names and to hasty descriptions of new forms, often based on inadequate material. As an example may be cited Cope's sending home from Wyoming by telegraph the descriptions of several new mammals in order that he might beat Marsh in publication. Owing to lack of erudition on the part of the telegraphers, the generic name *Loxolophodon* became transmuted into *Lefalophodon*, and other names fared little better.

The decade of the eighties was, in contrast with the previous period, one of gloom. The loss of his patrimony in injudicious investments reduced Cope to poverty, and made almost impossible the personal collection or acquisition of specimens. The various governmental surveys were consolidated into the United States Geological Survey, where, unfortunately for Cope, partisans of his rival Marsh were in control. This ended Cope's connection with governmental activities, and prevented the completion of his monumental work on the Tertiary vertebrates, of which one huge volume had already been printed, and the second planned. Even a great series of plates already prepared for this volume was not issued until two decades after his death. Further, while Cope was desperately in need of remunerative employment Marsh's enmity and fear

on the part of others of being drawn into the controversy rendered futile his attempts to obtain an appointment. The extracts from his letters of this period to his family, despite a superficial glaze of optimism, reflect the depression of his spirit.

During all this time, however, his scientific work continued without slackening, and a great array of valuable papers appeared from his prolific pen. The end of the decade saw an improvement of the financial situation with the appointment of Cope to Leidy's chair of comparative anatomy in the University of Pennsylvania, and the remaining years of his life passed in much happier circumstances. The fiery energy with which he worked, however, seems to have burned out his never strong body, and his career was cut short by death in 1897, at the age of fifty-seven years.

A considerable section of the book is devoted to an attempt to evaluate Cope's contributions to science, with discussions not only by Osborn, but by Scott, Gregory, and other authorities. His tireless enthusiasm resulted in the publication of a prodigious amount of work. This contains, it is true, many errors and generalizations too hastily drawn. But in most lines of paleontological research the foundations established by Cope, while altered and added to by subsequent workers, have proved sound, built as they were by a mind of broad vision and keen insight. The term "genius" is applicable to but few; of Cope, with his brilliance, energy, and catholic interests, the word may be used without reserve.

It is fitting that Cope's biographer should be Henry Fairfield Osborn, long a personal friend of Cope, as well as one who in many ways is to be regarded as his scientific successor. A concluding chapter of the work tells of the personal contacts of the two men, from the time in 1877 when Osborn and his classmate, William B. Scott, sought his advice when they started, as adventurous undergraduates, upon their careers as vertebrate paleontologists, to Cope's death two decades later. This personal knowledge and sympathetic understanding of his subject by the author is, perhaps, the principal factor which carries the book far beyond the ordinary scientific biographical memoir and gives us a vivid picture of an interesting personality rather than the usual mere recital of scientific achievements.

An annotated classified bibliography of Cope's principal papers, which completes the volume, is of considerable value. Cope's published writings comprise the astounding total of nearly 1,400 papers. Many of these, it is true, were short notes and reviews in his personal organ, the *American Naturalist;* but their brevity is more than compensated by such works as the ponderous "Cope's Bible," the *Vertebrata of the Tertiary Formations of the West,* with over one thousand quarto pages and eighty plates.

The volume lacks an index. Otherwise excellent, it is to be hoped that it will make known to a wide circle Cope the man as well as Cope the scientist.

A. S. R.

Chapters on the Geology of Scotland. By B. N. PEACH and JOHN HORNE. London: Oxford University Press, 1930. Pp. 232; figs. 27; pls. 18.

On their retirement from the service of the Geological Survey Drs. Peach and Horne decided to collaborate in the preparation of a book on the geology of Scotland, intended as their last gift to the science which they had so long and faithfully served. None could have written on this subject with fuller knowledge or deeper insight, but the crowning achievement of their lifelong labors was not to be granted. They spent some years in collecting material and in preparing a rough draft to be worked up later into final form. Pressure of other work and failing health, however, delayed their task. Peach died in January, 1926, and although Horne carried on alone, for him also the end came, two years later, with the book unfinished.

The volume now published under the title *Chapters on the Geology of Scotland* represents all that they were able to complete.

This statement in the Preface, by M. MacGregor, tells the story. A geology of Scotland by two such masters of their subject as Peach and Horne would have been a work of the greatest value in the geological world, and the pity is that they were not able to finish it. The five chapters which fortunately were completed are as follows: chapter i, "Physical Features of Scotland in Relation to Geological Structure"; chapter ii, "Pre-Cambrian Rocks: Lewisian Gneiss"; chapter iii, "Pre-Cambrian Rocks (continued): Torridon Sandstone"; chapter iv, "Cambrian System and Later Intrusions and Earth-Movements"; chapter v, "Highland Metamorphic Rocks, Moine Series (Eastern Schists)."

Two brief additional chapters on Islay and Colonsay and the north end of Jura and adjacent islands have been reproduced from the notes supplied by Dr. Peach to Dr. Horne as a basis for co-operation. They have been put in their present form by the three editors of this volume—M. MacGregor, E. B. Bailey, and R. Campbell.

The great care and thoroughness with which the areal occurrence, petrography, and structure of the formations have been worked out command the admiration of the reader. The slow evolution of interpretations reveals the difficult nature of many of the problems, upon some of which there is not yet unanimity of opinion. In general the authors have sought a maximum of fact and have been very restrained in their theoretical in-

terpretations. Their great strength lies in their lifelong, faithful gathering and assembling of field evidence.

No one chapter stands out noticeably above the others in interest or importance. To single out certain portions of the book for special comment is likely to be unfair to other portions. The oldest and most deformed rock system, the Lewisian gneiss, which is presumably the most difficult to decipher, stands out with surprising clarity. To this Sir John Flett has contributed a valuable report on the Archean rocks collected in the Isle of Lewis by Peach and Horne. The nature of the pre-Torridonian diastrophic movements is a welcome contribution. The Torridonian system is now satisfactorily understood in its main features. But the interpretation of the Moine schists is so much more obscure that it remained to the end a source of friendly disagreement between the two authors. Peach believed that the Moine schists are the metamorphosed representatives of the Torridonian; Horne, on the other hand, favored the hypothesis that the Moine consists of altered sediments, mainly of pre-Torridonian age, modified by post-Cambrian deformation. The latter view is favored in the final treatment.

The structural geologist, however, will be disappointed that the descriptions of the structures produced by the Caledonian deformation are not followed by a discussion of how they were developed. He will look in vain for a definite statement of the order in which the Glencoul, Ben More, Moine, and other great overthrusts occurred. Yet the order of occurrence is essential to an understanding of what actually took place. Had the authors lived to complete their great work this need might possibly have been supplied.

R. T. C.

The Geology of the Kalgan Area. By GEORGE B. BARBOUR. Member of the Geological Survey of China. (Ser. A, No. 6.) Peiping, 1929. Pp. 148; figs. 34; maps and cross-sections.

The city of Kalgan on the main trade route which leads from Peiping northwest into Mongolia is well known to many travelers. Lying near the base of the steep rise to the Mongolian plateau, Kalgan is in the midst of an area which belongs in part to the Mongolian plateau and in part to the low, mountainous region of Northern China. The important geological liaison between the areas to north and south offered by this district led to reconnaissance by the Geological Survey of China and the present report.

The pre-Cambrian is represented by two strongly unconformable systems, the Sangkan gneiss and the Nankou limestone, the latter belonging

to the Sinian system of Grabau (or Huto system of Willis and Blackwelder), and probably corresponding in age to the American Keweenawan and the Scottish Torridonian. The Sangkan is an injection gneiss formed during an epoch of intense pre-Cambrian deformation which gave its structure a northeast-southwest trend.

Paleozoic and early Mesozoic rocks are entirely wanting. At the close of the Jurassic came the Yenshan deformative movement which buckled the whole region into folds trending northeast-southwest, parallel to the pre-Cambrian foldings. In the later stages of the deformation the Kalgan porphyry lavas were poured over the edges of the pre-Cambrian formations. Erosion of the highlands yielded the continental Cretaceous Nantienmen formation. Continued erosion till late Oligocene time developed a peneplain upon which were poured the Hanoorpa basalts which floor much of the present Mongolian plateau. The Himalayan revolution was marked here only by uplift and block faulting.

The history of the region as outlined above has been very clearly established—partly from the study of the Kalgan area itself and partly from careful correlation with the work of other geologists both in Mongolia and Northern China. It impresses the reviewer, who has visited the region, as work distinctly well done. Next to the longest chapter of the report is the one on the evolution of the present land surface which contains much of interest to the geomorphologist.

Primary loess and "redeposited loess" are distinguished and mapped separately. It was the redeposited loess which led some earlier students to favor an aqueous origin of loess in general. Barbour has given an excellent picture of the mode of formation of the North China loess in its climatic setting.

R. T. C.

Microscopic Determination of the Ore Minerals. By M. N. SHORT. *United States Geological Survey, Bulletin 825.* Pp. 201; pls. 11; figs. 16. $0.50.

Determination of the Opaque Minerals. By C. MASON FARNHAM. New York: McGraw-Hill Book Co., Inc. Pp. 229. $3.50.

Lehrbuch der Erzmikroskopie. By H. SCHNEIDERHÖHN and P. RAMDOHR. Gebrüder Borntraeger. Volume II. Pp. 636; text figs. 7; pls. 235; colored pl. 1. Rm. 72.

During the year 1931 three books have appeared which will be of extraordinary value to economic geologists in the microscopic study of ores.

The titles of these are listed above, two being in English and one in German.

In the United States the splendidly equipped laboratories of Professor L. C. Graton at Harvard University are to be credited with instigating the first systematic formulation of criteria for the identification of opaque minerals in polished specimens under the reflecting microscope, and it is there, also, that the most refined methods of polishing and mounting have been developed. This may be said without disparagement of the valuable contributions of a less systematic character by workers in other Universities in the United States, in Canada, and in the United States Geological Survey. The earlier manuals of Murdock, and of Davy and Farnham, prepared under the auspices of the Harvard Laboratory, have after several years of useful service now been supplanted by Farnham's new manual and by Short's bulletin, the latter an outgrowth of his work at Harvard as a student and associate of Graton and of his subsequent labors in charge of the microscopic study of ores for the United States Geological Survey. These two books are sufficiently different in scope and method of presentation so that they supplement each other, and both will be indispensable to workers in this field.

Farnham's manual follows in general the plan of its predecessor by Davy and Farnham, but it is much more comprehensive. The backbone of the manual consists of over one hundred pages devoted to descriptions of the ore minerals arranged alphabetically—the descriptions covering their behavior with the usual reagents (HNO_3, KCN, HCl, $FeCl_3$, and KOH), composition, physical properties, and pertinent references to the literature. The thirty odd pages of determinative tables which follow enable the student to systematically run down these minerals by their reactions to these reagents and refer him to the preceding detailed descriptions. Supplementary tables classify the minerals according to distinctive color in the polished specimen, color of the powder, color of internal reflections, hardness, specific gravity, electrical conductivity, and reflecting power. Finally, characteristic reactions for the identification of various elements are given with determinative tables for the ore minerals that contain these elements.

Dr. Short's bulletin contains a much fuller account of the microscopes, lighting appliances, etc., used, and presents fully the various methods of polishing and of mounting as developed at Harvard, at the United States Geological Survey, and at the University of Minnesota. Sixteen pages are devoted to photomicrography. Methods of color comparison, testing of hardness under the microscope, and examination in polarized light are considered at some length. In the tables for determination the ore miner-

als are classed first as soft and hard and secondarily as isotropic and anisotropic, according to their behavior in reflected polarized light, and are further subdivided in accordance with their behavior with the same standard reagents listed above as used by Farnham. Page references refer the reader to more detailed descriptions. A particularly noteworthy and valuable feature of the bulletin is the eighty odd pages devoted to microchemical methods and a systematic scheme for microchemical analysis, concluding with specific tests for individual minerals. The microchemical section is illustrated with many excellent colored plates of characteristic precipitates. Microchemical tests have been considerably used by chemists and Short's work should make them more widely appreciated and used by the geologist.

The third book within the field of the microscopic study of ores is the *Lehrbuch der Erzmikroskopie*, by Professor Hans Schneiderhöhn, of the University of Freiberg, and Professor Paul Ramdohr, of the Technische Hochschule at Aachen. This volume of over seven hundred pages is a sequel to the *Anleitung zur mikroskopischen Bestimmung und Untersuchung von Erzen, etc.*, by Schneiderhöhn, published in 1922.

The new volume takes up *seriatim* the elements, simple sulphides, sulphosalts, strongly reflecting oxides and the common gangue minerals and oxidized ore minerals. Each mineral is exhaustively treated under the captions of its behavior and appearance on polishing, color and reflectivity, behavior in reflected polarized light, behavior with etching reagents, structure and texture, recognition, and paragenesis. Numerous halftones show the characteristic appearance and textural relationship of the various ore minerals in polished specimens. Four excellent plates in colors are included. Twenty pages are devoted to an exhaustive bibliography of over six hundred titles covering the literature on ore microscopy. The volume is indexed by minerals and by localities.

The nearly contemporaneous appearance of these three volumes marks the close of the pioneer period in the microscopic study of the opaque minerals and places its technique on a secure footing approaching that for the transparent rock-forming minerals.

E. S. B.

Addenda to Descriptions of Burgess Shale Fossils. By CHARLES D. WALCOTT. "Smithsonian Miscellaneous Collections," Vol. LXXXV, No. 3, 1931. Pp. 46; figs. 11; pls. 23.

The Burgess shale fossils have never ceased to be a source of wonder to even the most blasé paleontologists. It is therefore in the nature of very good news to learn that the study of this rich fauna, with its manifold

biologic problems, is not to lapse on account of the death of Dr. Walcott. Instead, because of the complexity of the various groups represented, it has been considered advisable to encourage a number of specialists to study the different classes. Thus papers by Dr. G. E. Hutchinson and Dr. Rudolf Ruedemann have recently been submitted. The present publication, however, comprises notes actually made by Dr. Walcott together with explanations by Dr. C. E. Resser.

The paper consists chiefly of 23 beautiful plates illustrative of a number of new as well as previously described genera and species; but there are also detailed descriptions and restorations of *Naraoia compacta*, *Burgessia bella*, *Waptia fieldensis*, *Skania fragilis*, and *Marrella splendens*. Although these bizarre arthropods (it is hazardous to refer them to previously known classes) seem almost like creatures out of some ancient *Alice in Wonderland*, they are so perfectly preserved that their entire ventral anatomy has been pretty definitely elucidated.

C. C.

Deutsches Erdoel. By BENTZ, HERRMANN, KRAISS, and STUTZER. Stuttgart: F. Enke, 1931. Pp. 150. M. 18, unbound.

This volume includes a contribution by each of the above-named authors on "Mesozoic Subsurface of the North-German Plain and Its Petroleum Possibilities," "The Geology of the Petroleum-Bearing Portion of the Cretaceous near Heide (Holstein)," "Petroleum at Oberg (near Peine)," together with a short introduction. The first paper calls attention to the "Pompecki swell," a subsurface higher province of the North-German plain, above which the Hannover marine Jurassic and Lower Cretaceous petroleum horizons are missing.

D. J. F.

Bernstein (*Amber*). By L. SCHMID. Dresden: T. Steinkopff, 1931. Pp. 103. M. 7, unbound.

This is a section from the *Handbuch der Mineralchemie* of Doelter-Leitmeier. Noteworthy is a bibliography of 613 titles, split into divisions following the various chapters.

D. J. F.